TEVATRON Collider Luminosity Upgrades

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Joint Experimental Theoretical Physics Seminar

Run II Luminosity Goals

- The luminosity goal for Run IIa is 2 fb^{-1}
  - Peak luminosity up to $2x10^{32}$ $cm^{-2}sec^{-1}$
  - Switch to 103 bunches at $1x10^{32}$ $cm^{-2}sec^{-1}$
  - Length of Run IIa is about 2 years

- The luminosity goal for Run IIa+Run IIb is 15 fb^{-1}
  - Increase antiproton intensity by 2-3
  - Peak luminosity up to $5x10^{32}$ $cm^{-2}sec^{-1}$
  - 103 bunch operation
  - Length of Run IIb is about 4 years

Run II Parameters

RUN	Ib (1993-95) (6x6)	Run IIa (36x36)	Run IIa (140x105)	Run IIb (140x105)	
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}	2.7×10^{11}	
Antiprotons/bunch*	5.5×10^{10}	3.0×10^{10}	4.0×10^{10}	1.0×10^{11}	
Total Antiprotons	3.3×10^{11}	1.1×10^{12}	4.2×10^{12}	1.1×10^{13}	
Pbar Production Rate	6.0×10^{10}	1.0×10^{11}	2.1×10^{11}	5.2×10^{11}	hr^{-1}
Proton emittance	23π	20π	20π	20π	mm-mrad
Antiproton emittance	13π	15π	15π	15π	mm-mrad
β*	35	35	35	35	cm
Energy	900	1000	1000	1000	GeV
Antiproton Bunches	6	36	103	103	
Bunch length (rms)	0.60	0.37	0.37	0.37	m
Crossing Angle	0	0	136	136	μrad
Typical Luminosity	0.16×10^{31}	0.86×10^{32}	2.1×10^{32}	5.2×10^{32}	$cm^{-2}sec^{-1}$
Integrated Luminosity†	3.2	17.3	42	105	pb^{-1}/week
Bunch Spacing	~3500	396	132	132	nsec
Interactions/crossing	2.5	2.3	1.9	4.8	

†The typical luminosity at the beginning of a store has traditionally translated to integrated luminosity with a 33% duty factor. Operation with antiproton recycling may be somewhat different.

Luminosity Formula

$$\mathrm{L} = \frac{3\gamma f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*, \theta_{x,y}, \varepsilon_{p,\bar{p}}, \sigma^L_{p,\bar{p}}\right)}{\left(1+\varepsilon_{\bar{p}}/\varepsilon_p\right)}$$

The major luminosity limitations are

- The number of antiprotons ($BN_{\bar{p}}$)
- The proton beam brightness (N_p/ε_p)
- F<1

Limitations on the Proton Brightness

- At the collision points, the magnetic field of the proton beam affects the pbar beam (and vice-versa)

Quadrupole Term

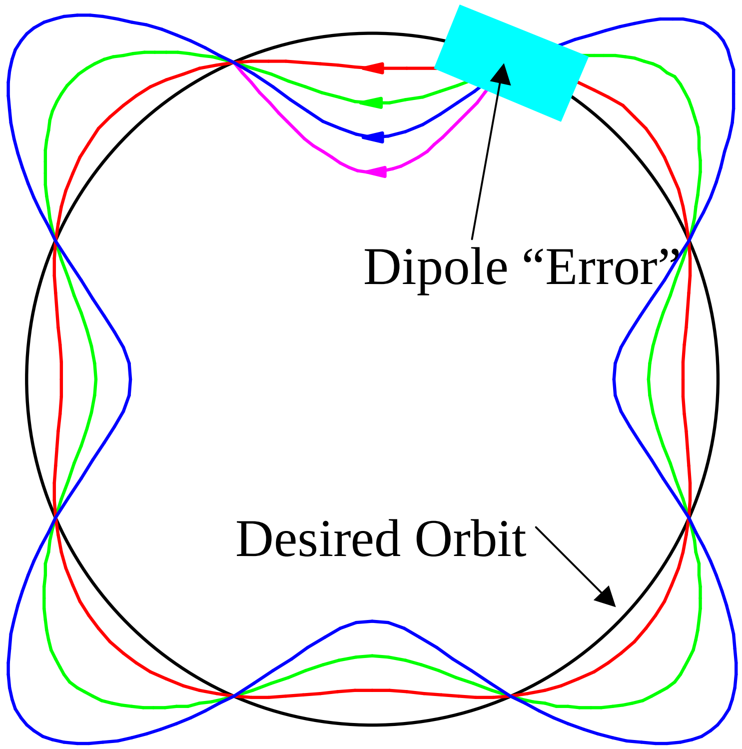
$$B(x) = B_o + B_1 x + B_2 x^2 + B_3 x^3 + \ldots$$

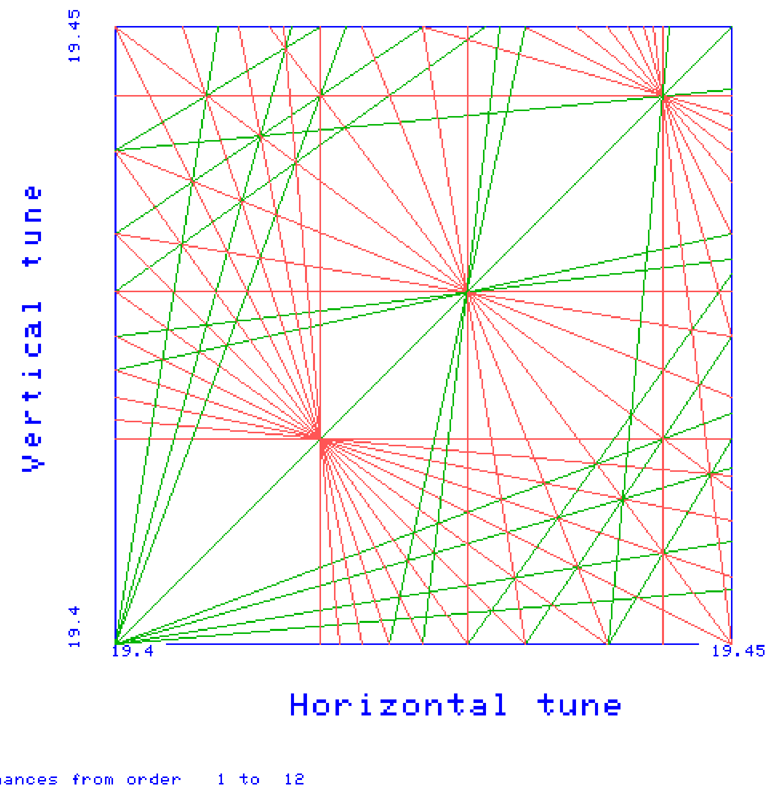
Dipole Kick

Amplitude dependent
Quadrupole Terms

- Dipole terms change the closed-orbit
- Quadrupole terms change the focussing which changes the betatron tune (the number of transverse "wiggles" that a particle will make going around the synchrotron once).

Resonance Lines



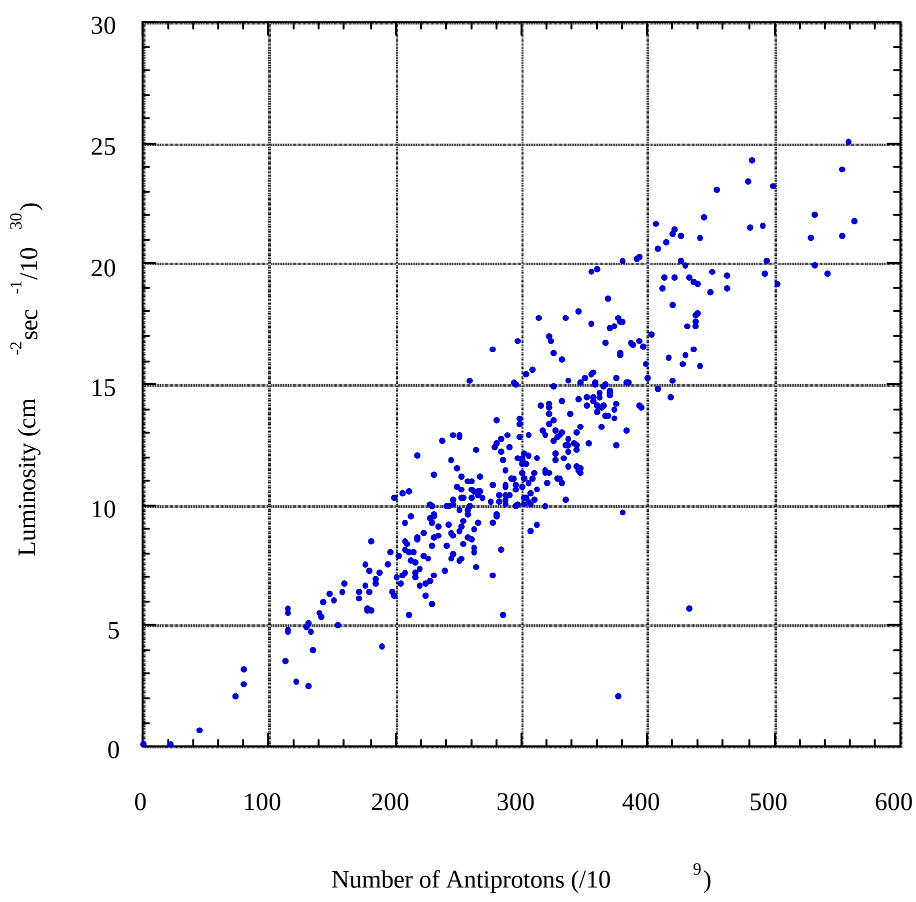


- Dipole errors affect tunes = 1, 2, 3…
- Quadrupole errors affect tunes 1/2, 1, 3/2, 2, 5/2 ...
- Sextupole errors affect tunes 1/3, 2/3, 1, 4/3...

Beam-Beam Tune Shift

- Since the proton beam is usually much stronger than the pbar beam:
  - The higher order terms of the magnetic field expansion of the proton beam will result in a betatron tune that is a function of each pbar's betatron amplitude.
  - The size of this tune "spread" will be proportional to the proton beam current.
  - The number of protons is limited to the point to where the pbar tune-spread crosses a given resonance.
- The proton intensity in the Run IIa parameter list pushes the beam-beam tune shift limit (not to mention long-range interactions!)

Luminosity vs. Antiproton Intensity



The Run IIb Plan

Increase the number of antiprotons in the collider by a factor of 2-3 over Run IIa

- without major interruption to Run IIa
- within a period of 2-3 years
- with a modest budget
- with a relatively small number of people

More Antiprotons

- More protons on the antiproton target (~1.8 x)
  - Slip stacking
    - MI Beam loading compensation
    - Booster Cogging
    - Proton beam sweeping
  - Brighter Proton Source
    - Brighter Ion Source
    - New Linac front-end acceleration stage

More Antiprotons

- Better antiproton collection efficiency
  - Lithium lens Upgrade(~1.5 x)
    - Solid lens redesign
    - Liquid Lithium lens
  - AP2-Debuncher aperture increases (~1.5 x)
    - Physical aperture increases and beam based alignment
    - Debuncher lattice Upgrades

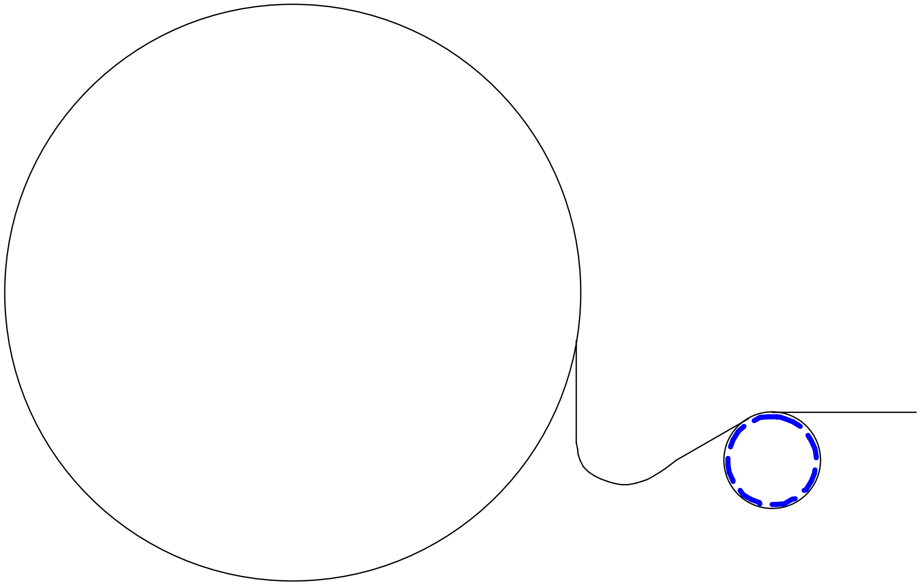
Handling the Increased Antiproton Flux

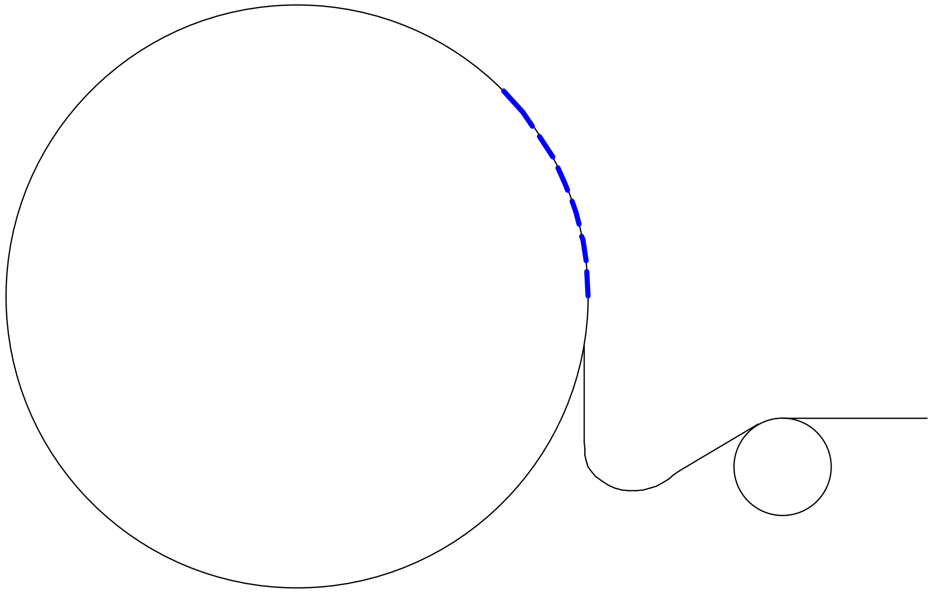
- Better cooling
  - Debuncher cooling bandwidth increase
  - Accumulator Stacktail
    - Gain slope redesign
    - Betatron Cooling
  - Accumulator Core bandwidth and sensitivity increase
  - Electron cooling in the Recycler
- Better Antiproton Transfer Efficiency
  - Dedicated Accumulator to Recycler 8 GeV transfer line (AP5)

Slip Stacking

- Increases the number protons on the antiproton target
  - The intensity of the Proton Source is limited by space charge tune shift at 400 MeV (and other things)
  - The available longitudinal phase space in the Main Injector is enormous.
    - Momentum aperture
    - Circumference
  - Slip stacking combines two booster batches into a single batch.
- Advantages
  - Not a large construction project - mostly RF electronics
  - Can be used to increase NUMI intensity
- Disadvantages
  - Requires high gain beam loading compensation
  - Bunch length on the pbar target is increased
  - Losses in the Main Injector may be higher

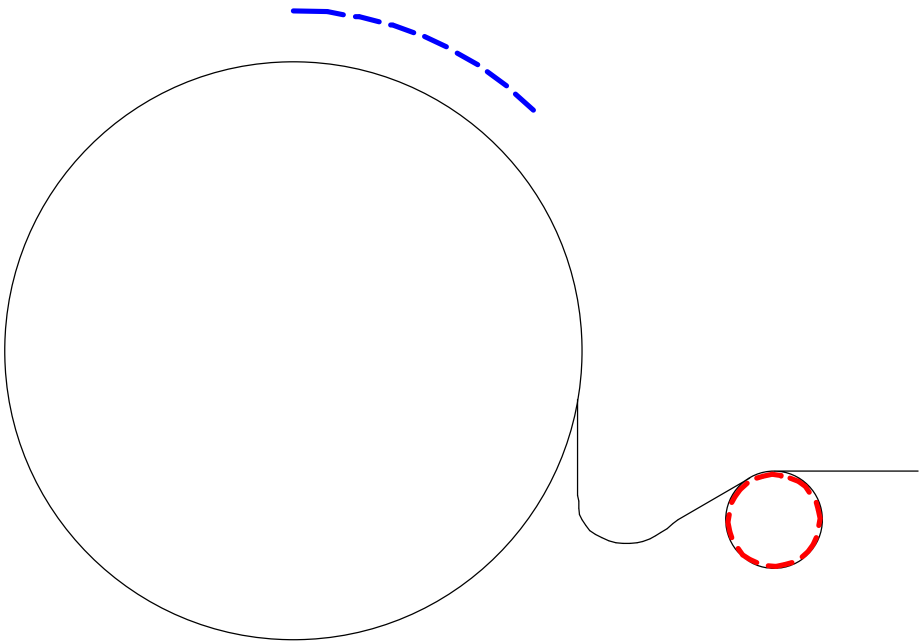
Slip Stacking

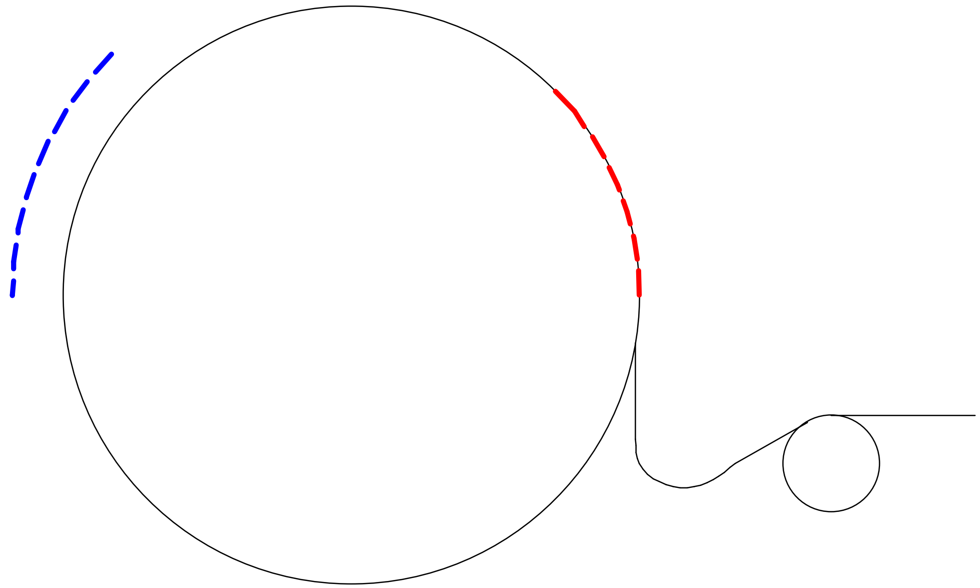




- First Booster Batch accelerated in Booster
- First Booster Batch injected onto MI central orbit with RF system **A**

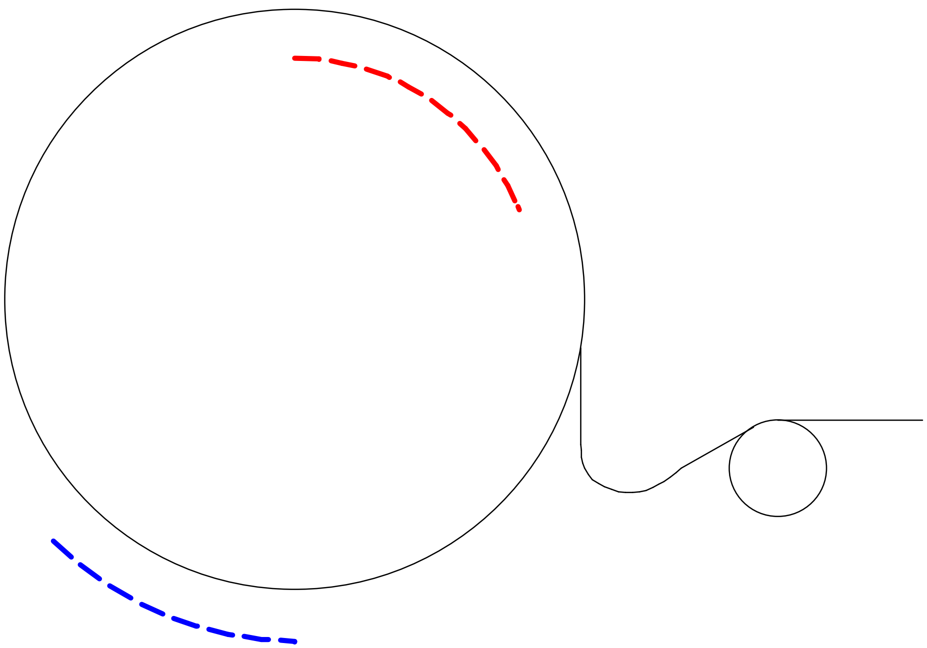
Slip Stacking

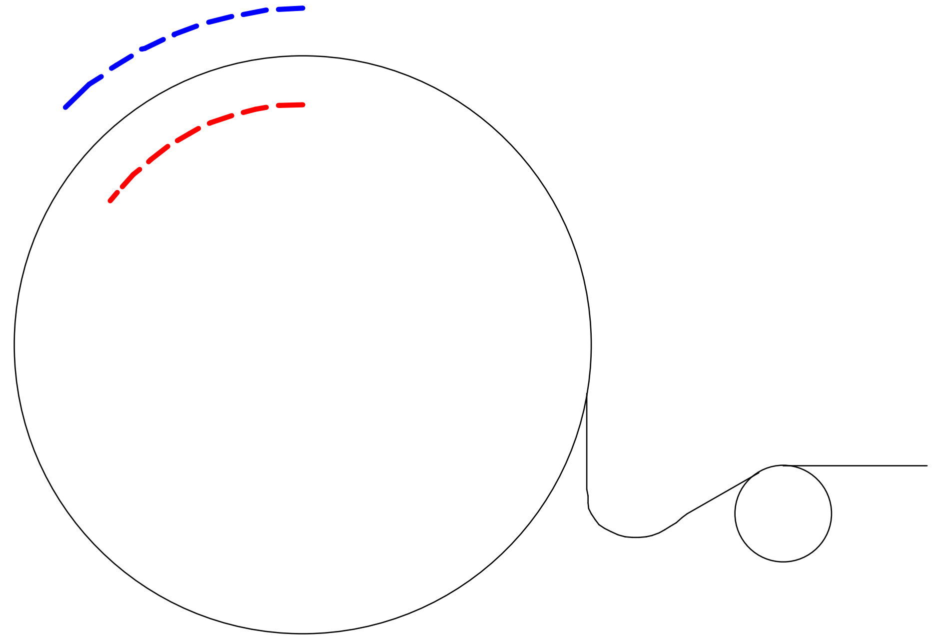




- First Booster Batch slightly accelerated in MI with RF System **A**
- Second Booster Batch accelerated in Booster
- Second Booster Batch injected onto MI central orbit with RF system B

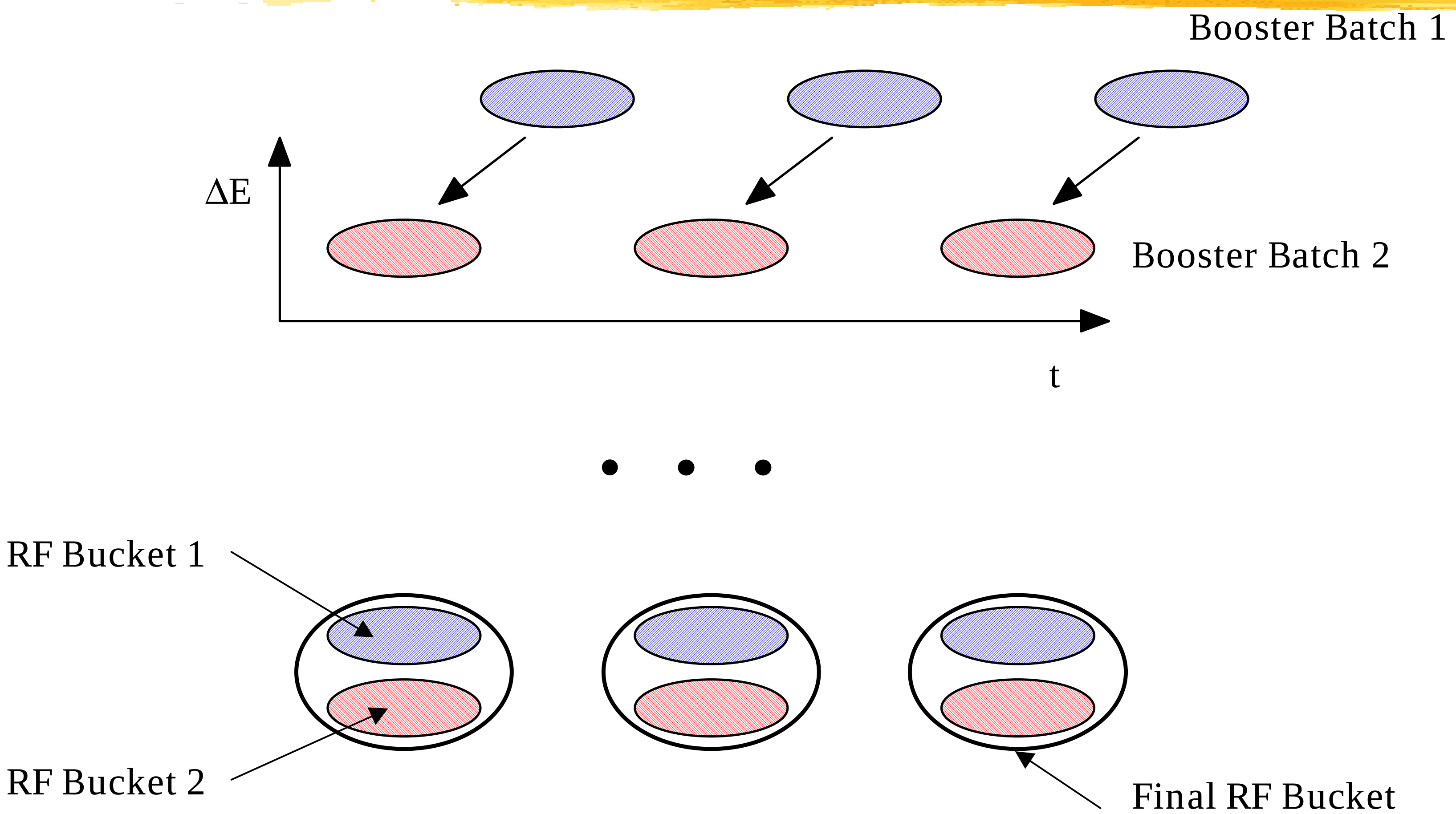
Slip Stacking





- Second Booster Batch slightly decelerated in MI with RF System B
- Wait till batches line up and snap on RF system C while turning of RF systems A & B

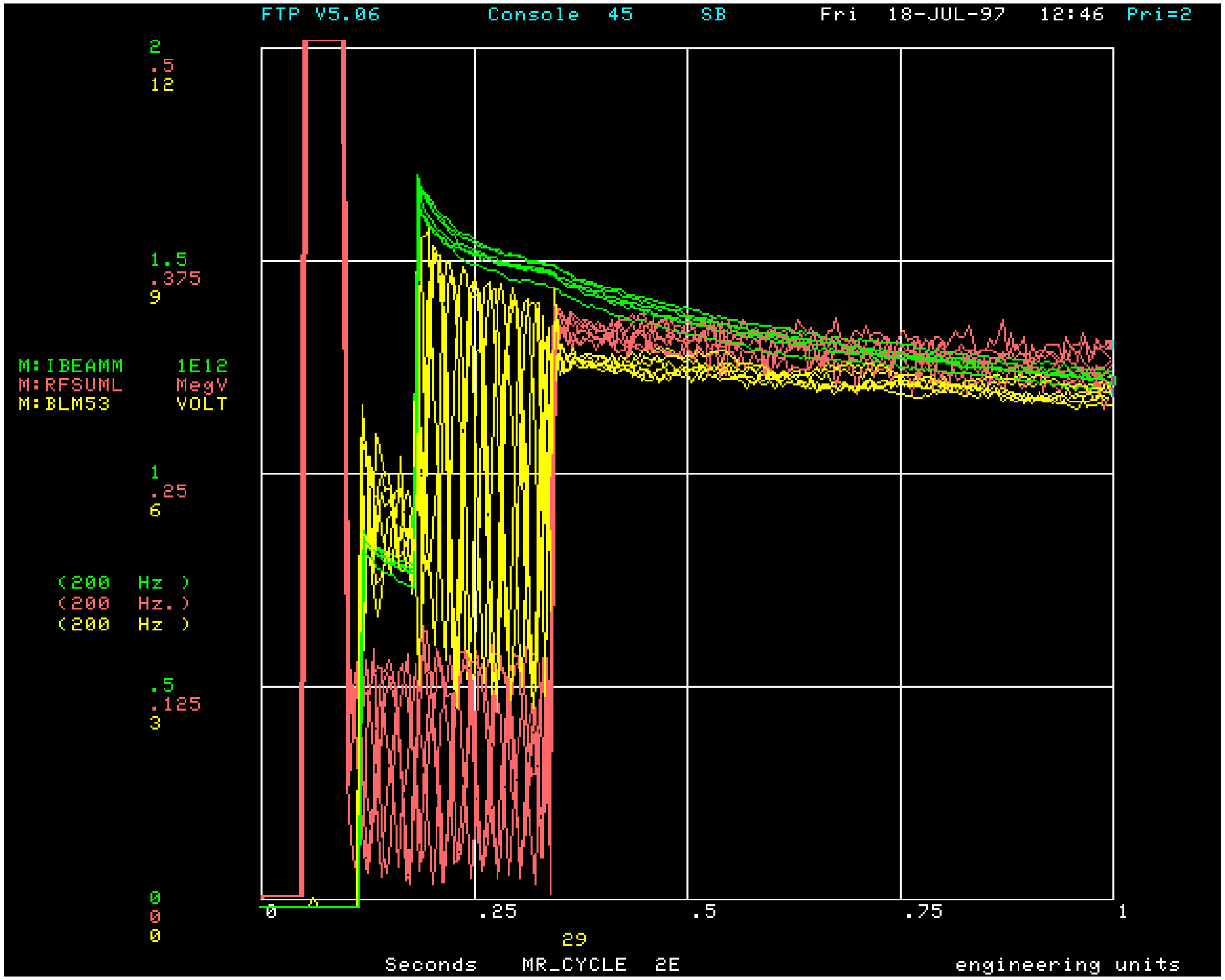
Slip Stacking



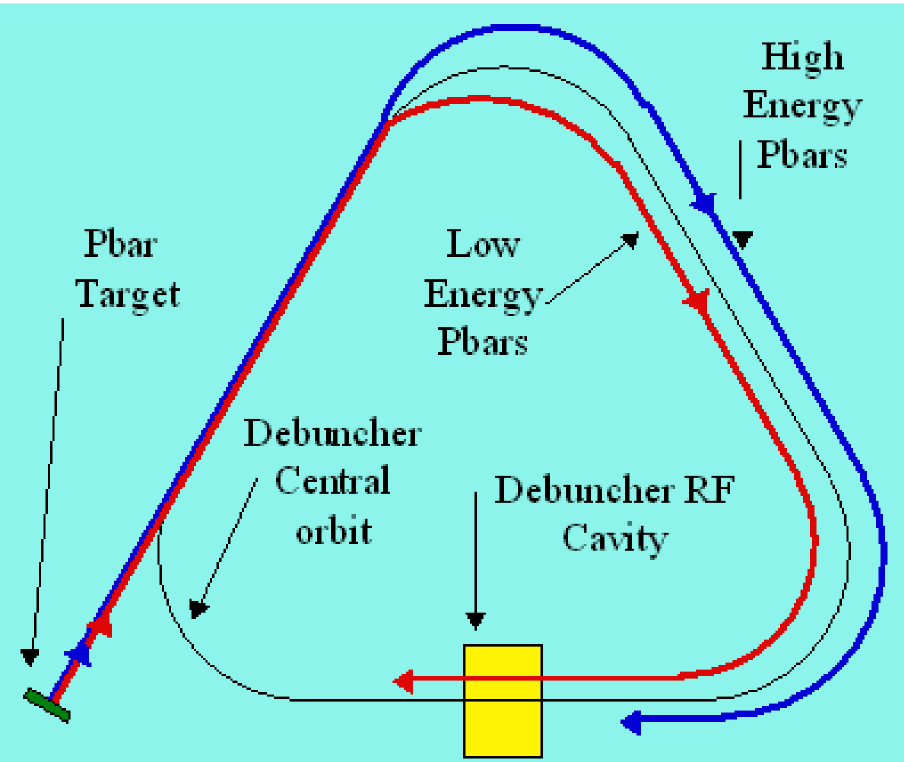
RF Phase Space Cartoon

Slip Stacking Experiment in the Main Ring

M:IBEAM=beam current (dc)
M:RFSUML=rf voltage fanback
M:BLM53=beam current at 53 MHz



The Debuncher Longitudinal Phase Space

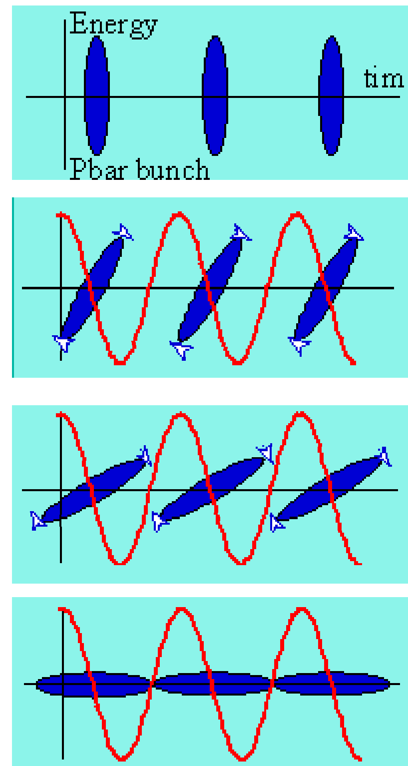


Pbars right after the target

Pbars arriving at the RF cavities

Pbars after many turns through the RF cavities

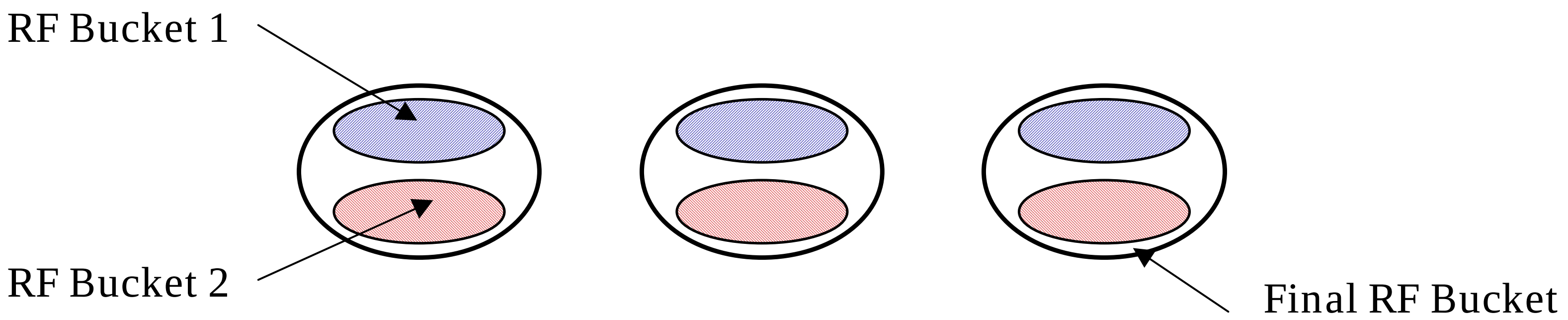
Pbars at the end of debunching



- The bunch length on the target must be as short as possible to minimize the final momentum spread in the Debuncher and the initial momentum spread on the StackTail Injection orbit.

Longitudinal Emittance and Slip Stacking

- To obtain a short bunch length, the longitudinal emittance of the proton bunches should be small as possible.
- A small longitudinal emittance requires that energy separation between the A & B batches be as small as possible during the final capture.
- The small energy separation requires that the RF buckets of the A & B batches not overlap
- The bucket heights which is proportional to the RF voltage must be very small.



Beam Loading

- Low Frequency (< 100 MHz) RF power sources, such as tetrodes, are typically current sources.
- The particle beam is accelerated with an electric field or a "voltage" gradient.
- An RF cavity can be thought of as a narrow band transformer that converts current to voltage.
  - The larger the cavity impedance, the more voltage that can be obtained for the same RF power.
- The particle beam travelling through the RF cavity is also a "current" source (especially at these energies).

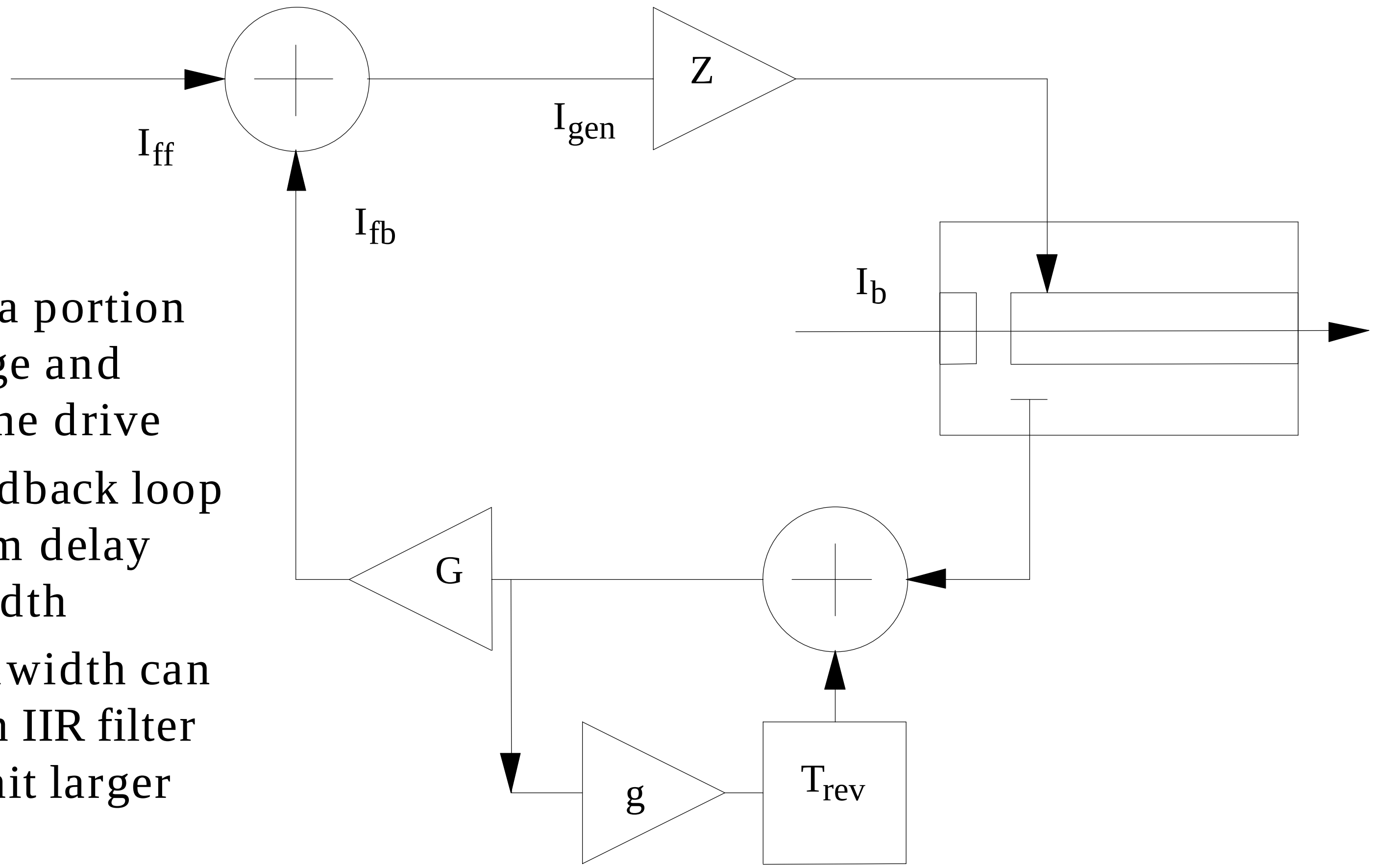
Beam Loading

- The particle beam current source also induces a voltage in the cavity
  - The stronger the beam current , the larger the voltage or wakefield induced in the cavity.
  - The fundamental frequency of the beam induced voltage will be the same as the accelerating voltage.
  - The beam induced voltage will be out of phase with the accelerating voltage
  - If the bunch train of the beam does not fill the entire machine, the envelope structure of the beam induced voltage will not match the accelerating voltage

Beam Loading

- Because the cavity has a finite bandwidth (the narrower the bandwidth, the larger the impedance), the beam induced voltage will "ring" or persist in the cavity after the beam has left the cavity.
- The beam induced voltage will change the energy of following bunches in a non-uniform way
  - Longitudinal emittance growth
  - Beam loss
- The ratio of beam-induced voltage to accelerating voltage during slip-stacking will be somewhere between 3-10.

Beam Loading Compensation using Direct RF Feedback

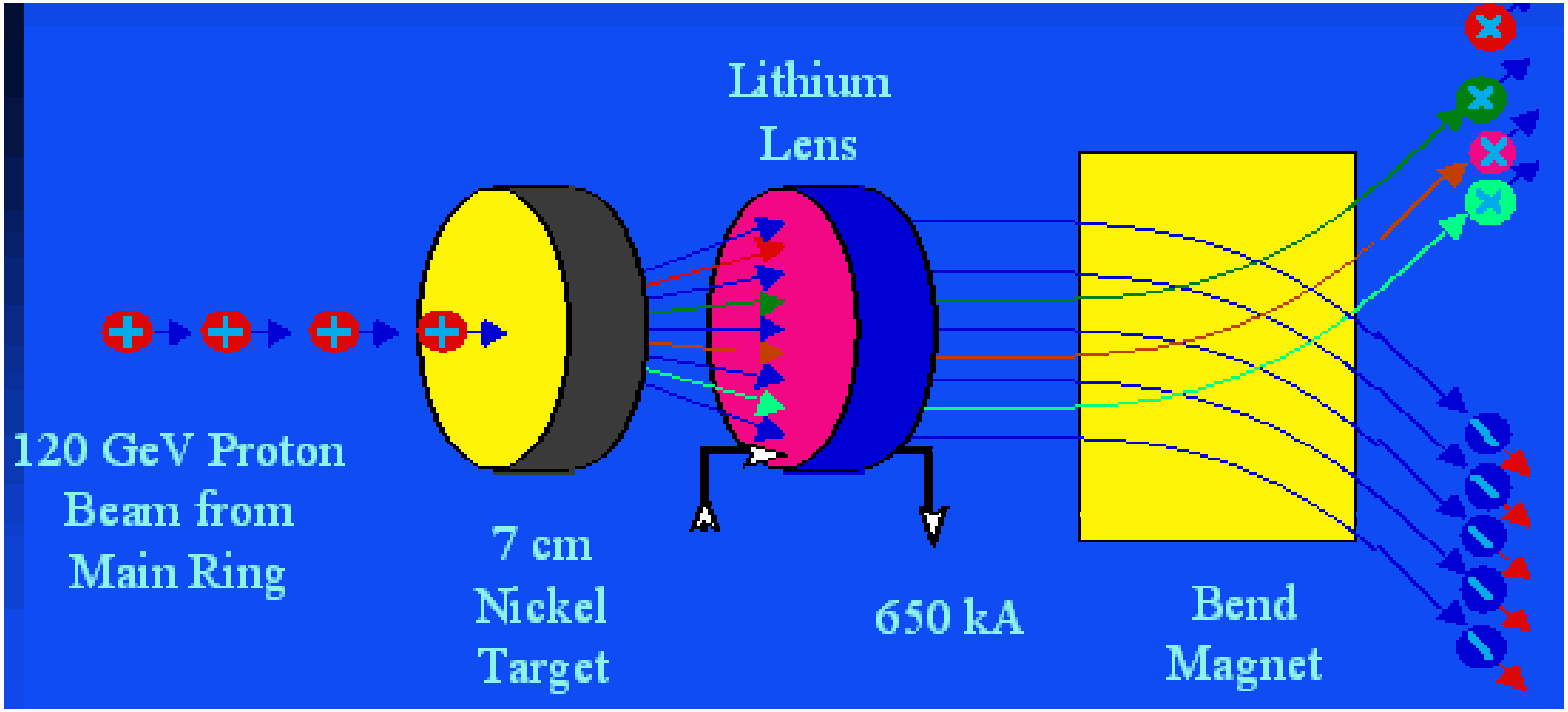


- RF feedback takes a portion of the cavity voltage and feeds it back into the drive
- The gain of the feedback loop is limited by system delay and cavity bandwidth
- The feedback bandwidth can be reduced with an IIR filter which would permit larger gains

Beam Loading Compensation

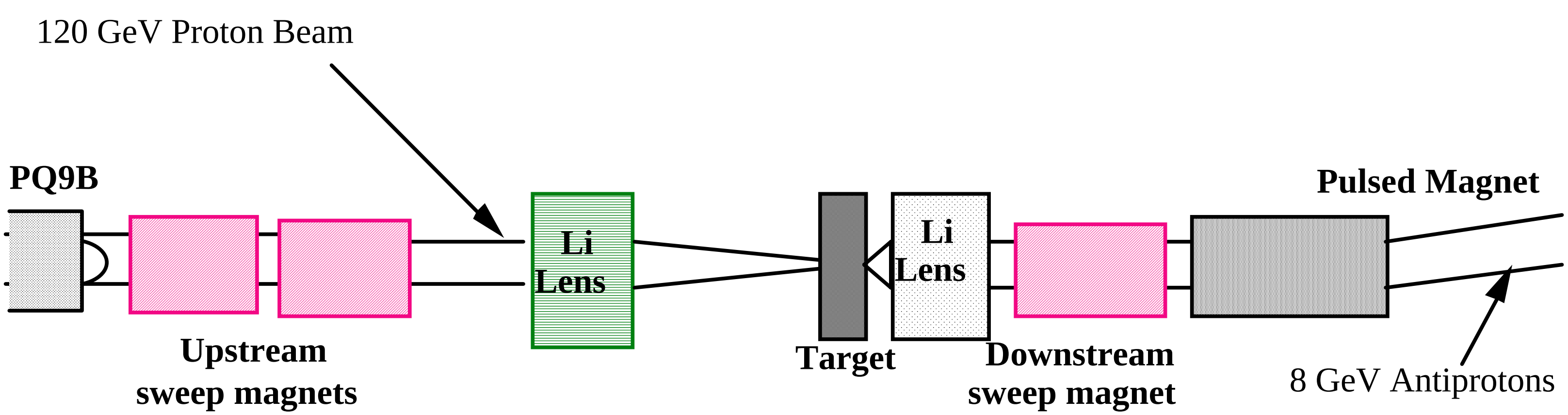
- Present project underway to incorporate direct RF feedback in all 18 Main Injector 53 MHz RF cavities
  - 1st phase - feedback at the fundamental mode lines
  - 2nd phase - feedback at fundamental and first mode lines
  - 3rd phase - feedback at more mode lines using a digital IIR filter
- Beam loading compensation will also help:
  - RF Coalescing for the collider
  - Pbar production cycles
    - Injection
    - Transition
    - Bunch Rotation
  - High intensity Fixed Target running (NUMI)

Pbar Target Station



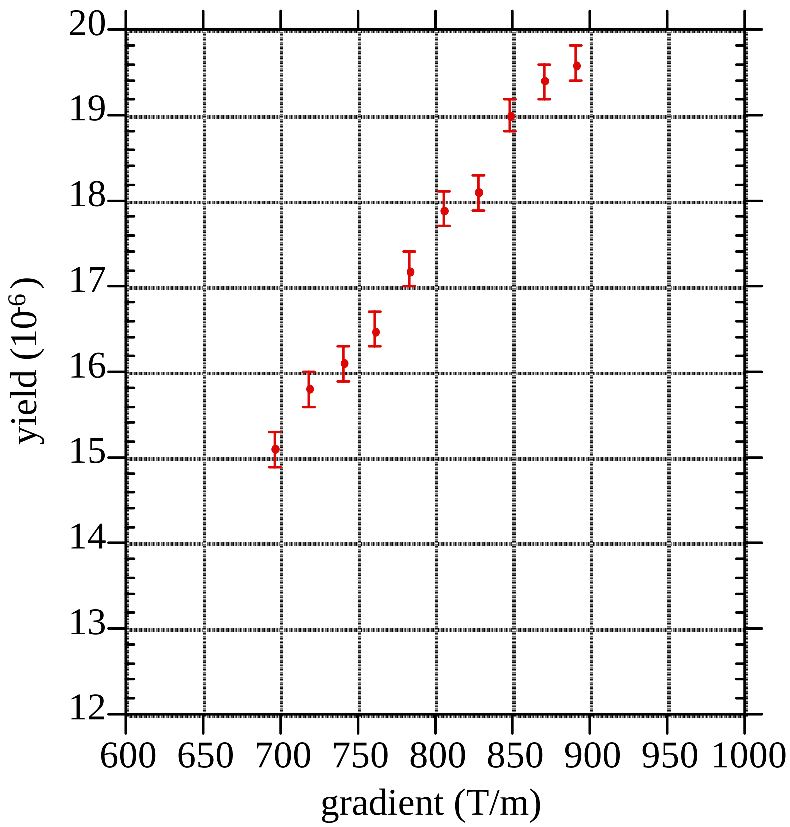
Beam Sweeping at the Antiproton Production Target

- As the intensity of the proton beam on target increases, the peak energy deposition of the proton beam at the target is high enough to damage the target in a single pulse

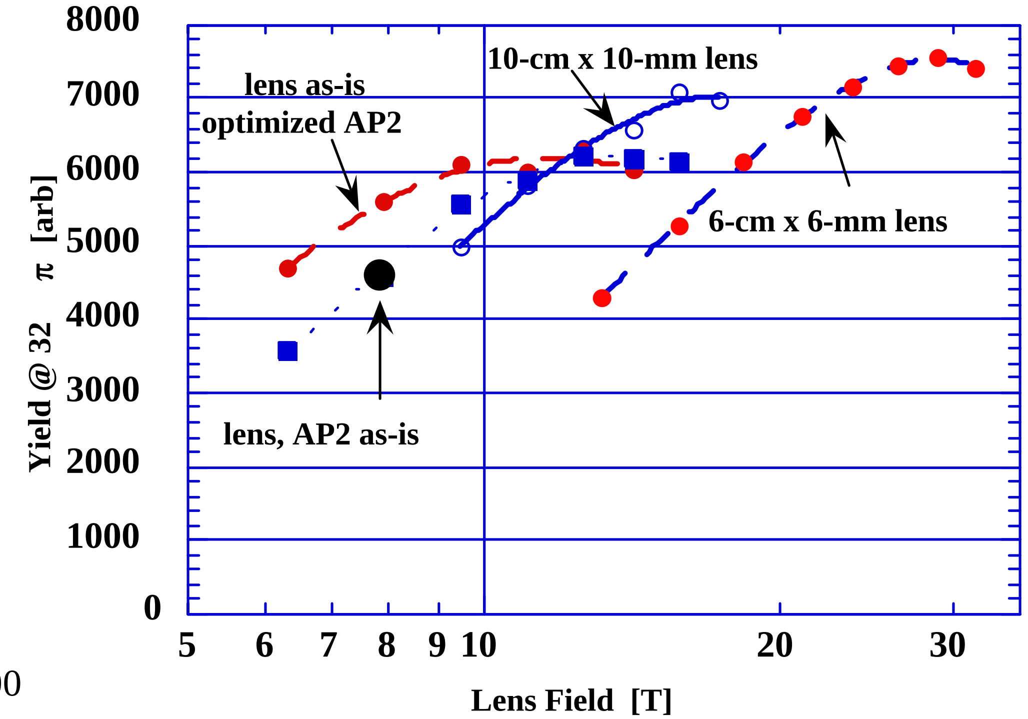


Lithium Lens Gradient Upgrade

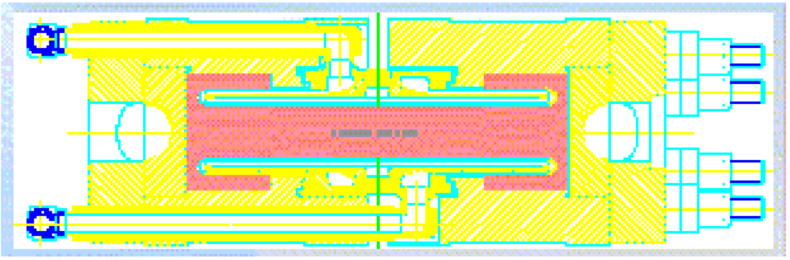
Solid Lens Performance



Lens Predictions

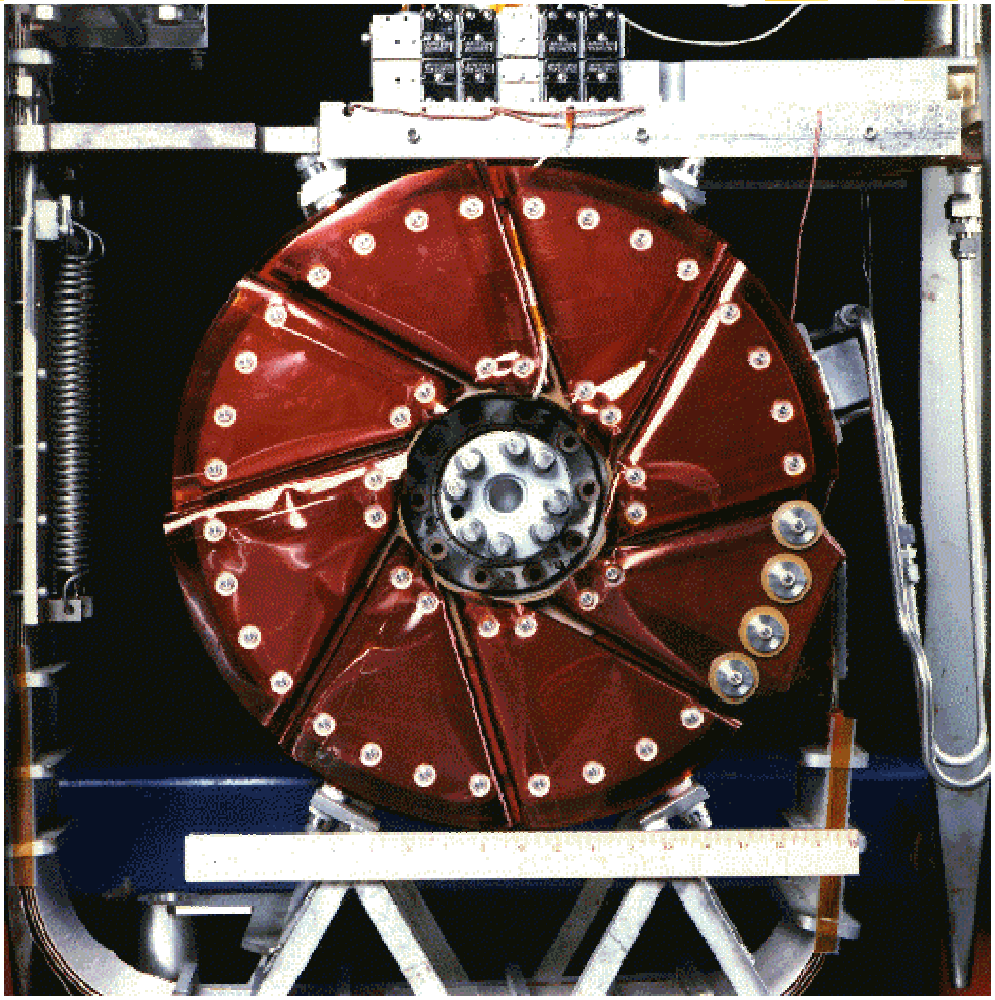


Lithium Lens



Cross-section of lithium lens Body

Picture of lithium lens in transformer

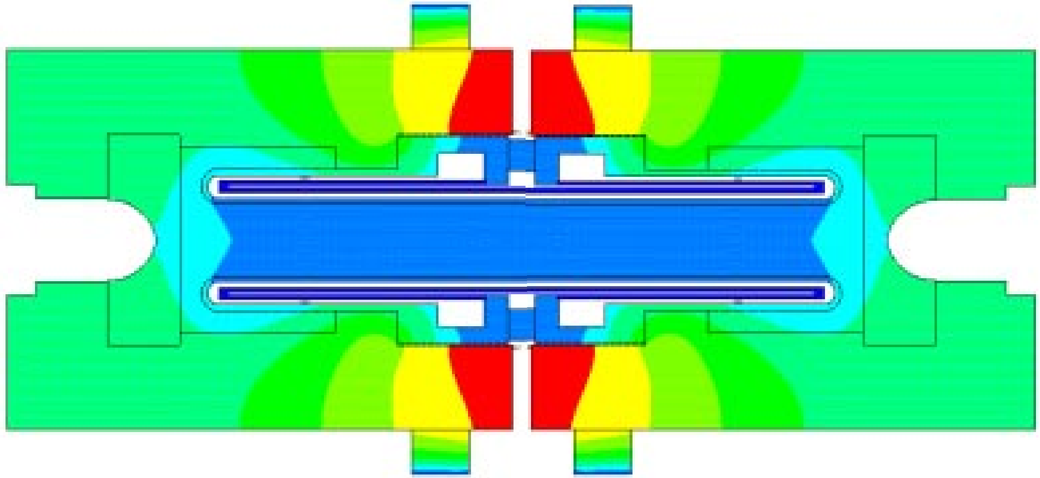


Solid Lens Upgrade

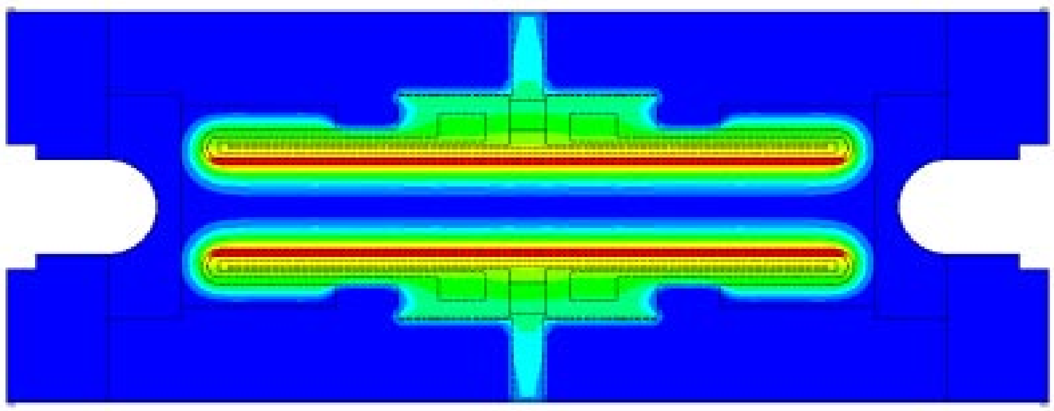
- TEV 1 design gradient was 1000 T / m
- Catastrophic failures due to component fatigue limits the present gradient to 760 T / m
- Upgrade present lens design to obtain 1000 T / m
  - New fabrication techniques
    - Diffusion bonding, etc.
  - New materials
  - Package re-design
    - better cooling, etc.
  - Lens parameter changes
    - radius, etc. - **CDF P. Bussey**

Solid Lens ANSYS models

Temperature Profile



Magnetic Field Profile



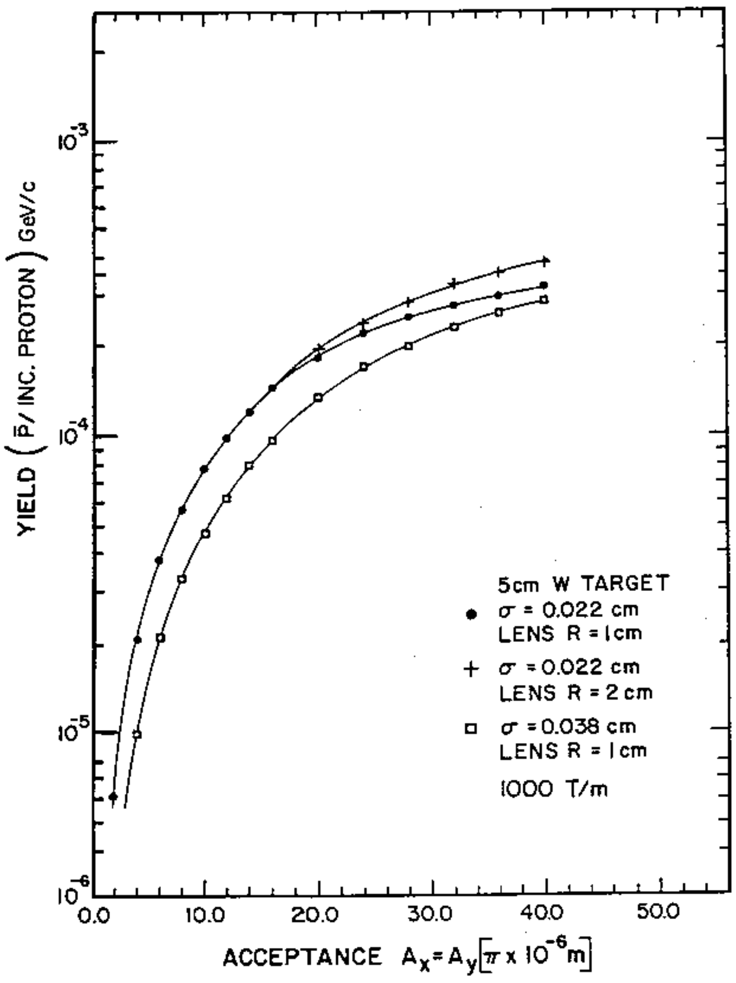
Courtesy of Zhijing Tang

BINP Liquid Lithium Lens Prototype

Antiproton Aperture Increases

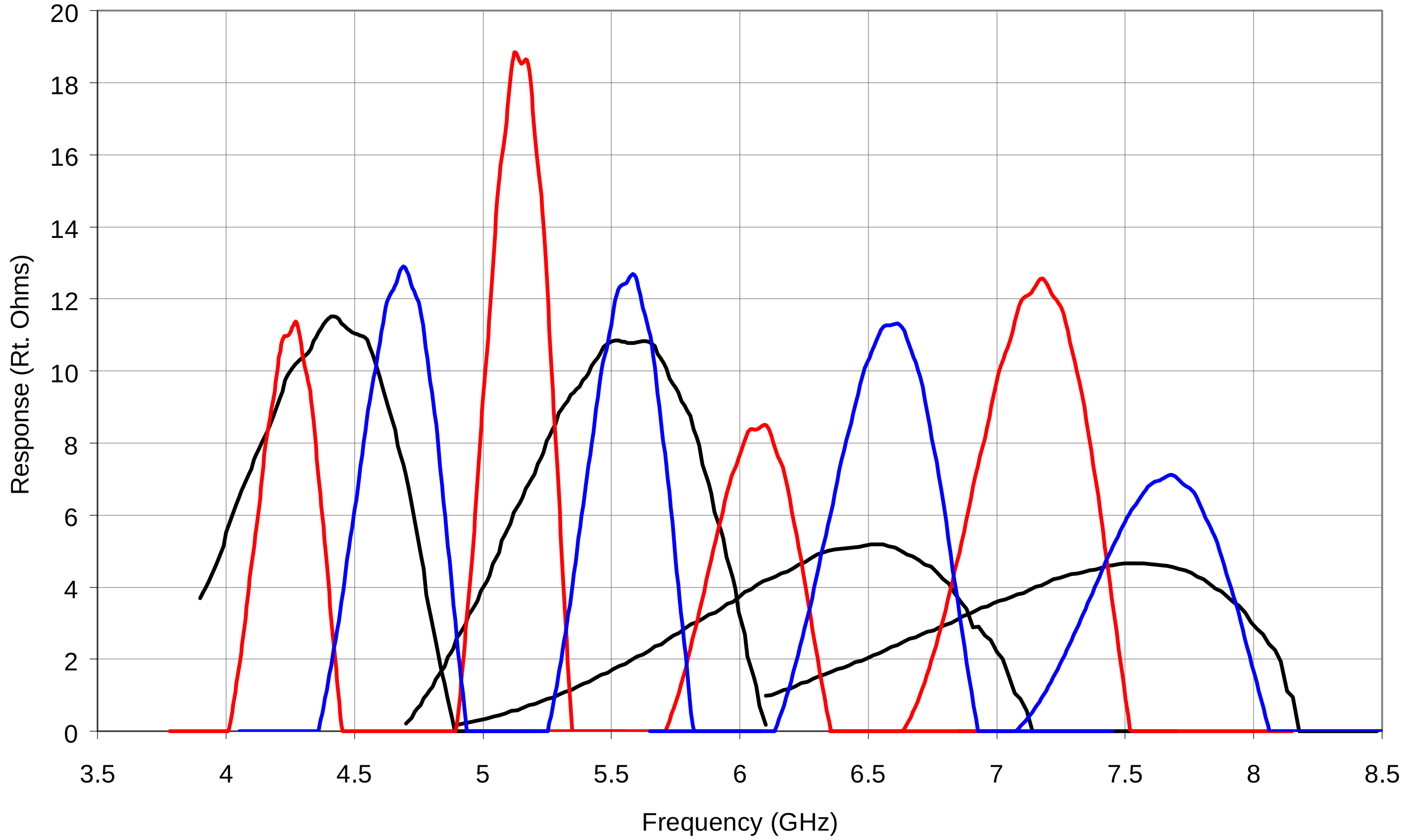
- Increase aperture in regions upstream of the first stage of stochastic cooling
  - AP2 transfer line
  - Debuncher
- The goal is to increase the aperture in both planes from 25π mm-mrad to 40 π mm-mrad
- Beam based alignment of all magnetic elements
  - requires new instrumentation **CDF R. Hughes, B. Winer, A.Semenov**
  - motorized quads
- Physical aperture increases
  - such as replacing beam pipe in Debuncher dipoles with curved beam pipe

TEV 1 Antiproton Yield vs. Acceptance

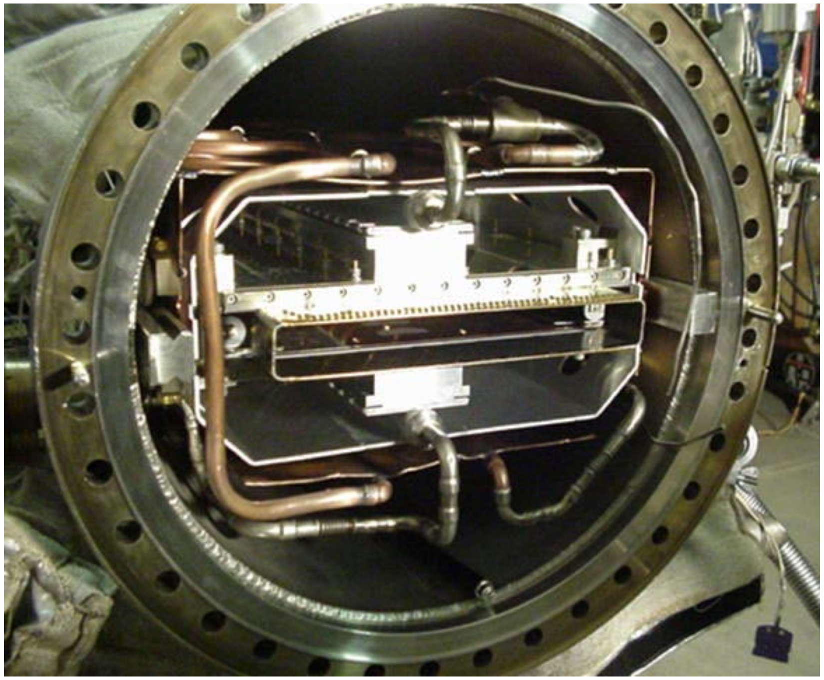


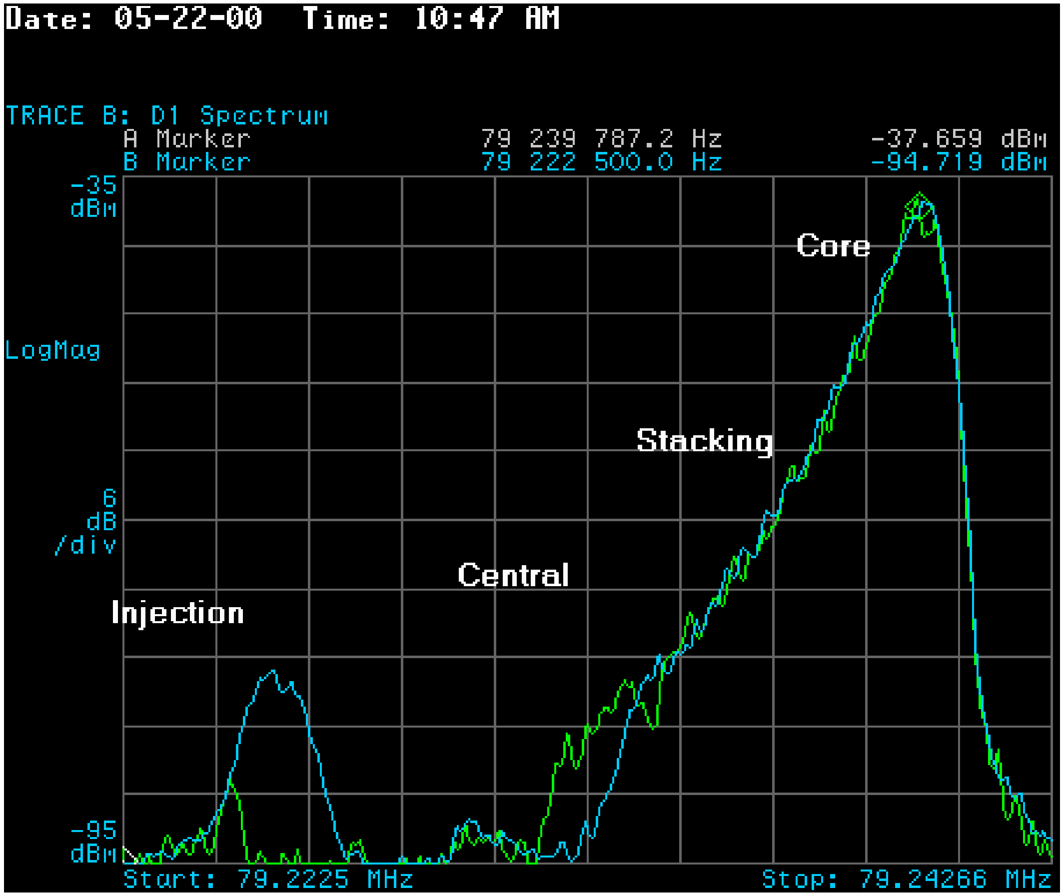
Debuncher Cooling Cryogenic Multiband Cooling Systems

- Narrow high sensitivity bands for low intensity
- Wide low sensitivity bands for high intensity



Accumulator Stacktail Stochastic Cooling Cooling System



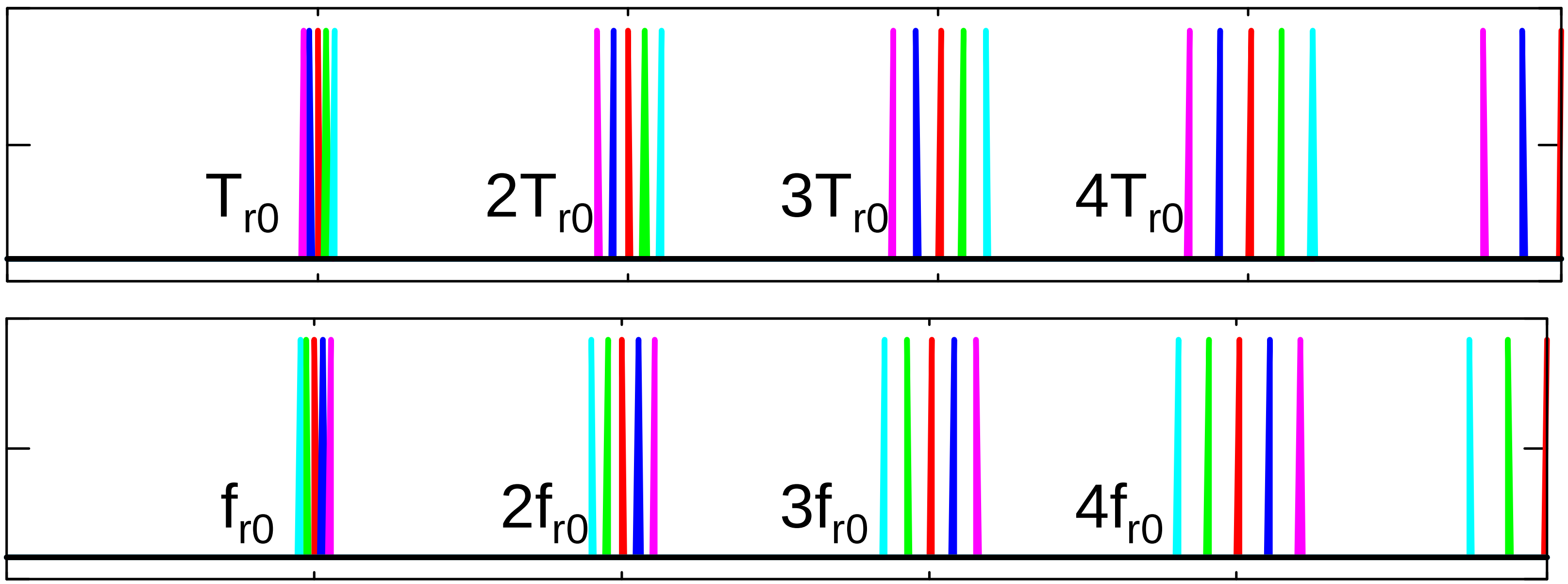


Accumulator Stacktail Stochastic Cooling Cooling Gain Profile

$$\Phi_0 = \frac{|\eta|}{4} \frac{W^2}{f_0} \frac{E_d}{pc} \frac{1}{\ln\left(f_{max}/f_{min}\right)}$$

- The stacktail system bandwidth was doubled for Run IIa
  - Microwave systems with fractional bandwidths greater than an octave are difficult to design
  - The StackTail bandwidth was changed from 1-2 GHz to 2-4 GHz for Run IIa
- With the Run I Accumulator lattice, the StackTail schottky bands overlapped above 3 GHz.
- The Accumulator lattice was changed (η went from 0.022 - 0.012) so that the schottky bands would not overlap in the Run II 2-4 GHz system
- The flux that the StackTail could accommodate was doubled.

Schottky Band Overlap



$$-\eta\frac{\Delta pc}{pc} = -\frac{\Delta T_r}{T_r} = \frac{\Delta f_r}{f_r} = \frac{\Delta hf_r}{hf_r}$$

2-4 GHz Accumulator Stack Tail System

$$\Phi_0 = \frac{|\eta|}{4} \frac{W^2}{f_0} \frac{E_d}{pc} \frac{1}{\ln\left(f_{max}/f_{min}\right)}$$

- The bandwidth of the StackTail system will not be increased for Run IIb
  - It would be extremely difficult to change the Accumulator lattice again.
  - Stochastic cooling systems with the frequency range above the cutoff frequency for the beam-pipe are very difficult to build
- The increased flux will be handled by doubling the characteristic energy E_d of the StackTail System
  - Doubling E_d is accomplished by halving the gain slope of the StackTail system.
    - Halving the gain slope is done by increasing the vertical aperture of the StackTail Pickups
    - Larger Aperture will reduce the signal to noise of the system so that LHe pickups will probably be necessary.

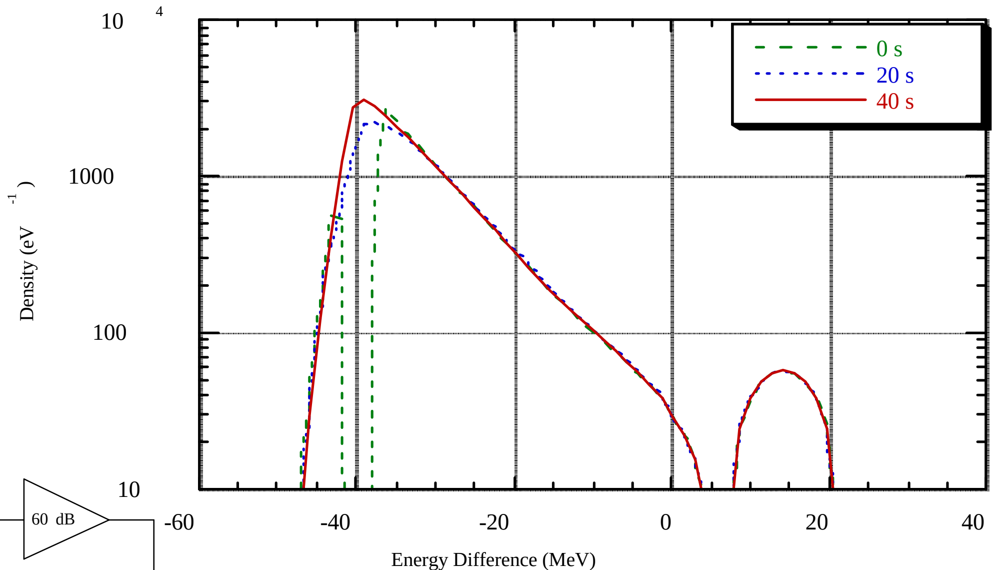
Limits on Accumulator Stack Size

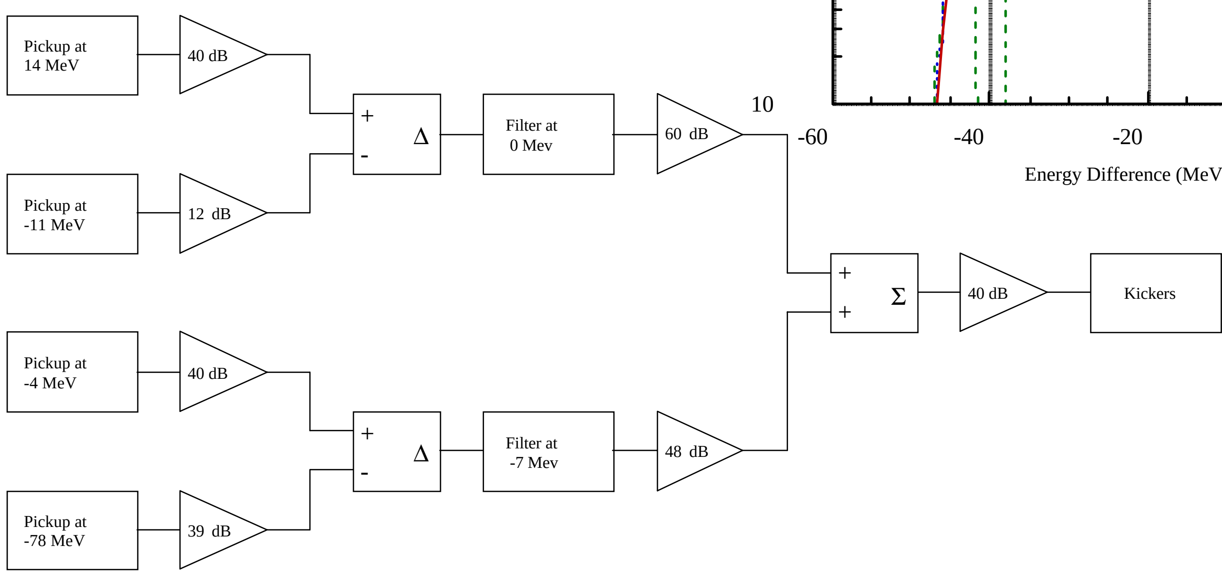
- If :
  - The gain slope of the Stacktail system is halved
  - The momentum aperture of the Accumulator remains fixed
- the amount that the Accumulator core can accumulate is dramatically reduced.
- The Accumulator Core must be removed every few minutes (5-10 min.) from the Accumulator.

The Recycler MUST WORK

2-4 GHz Accumulator Stack Tail System

- 5.6x10^8 antiprotons / 2 sec
- Transfers to the Recycler every few minutes (~5)





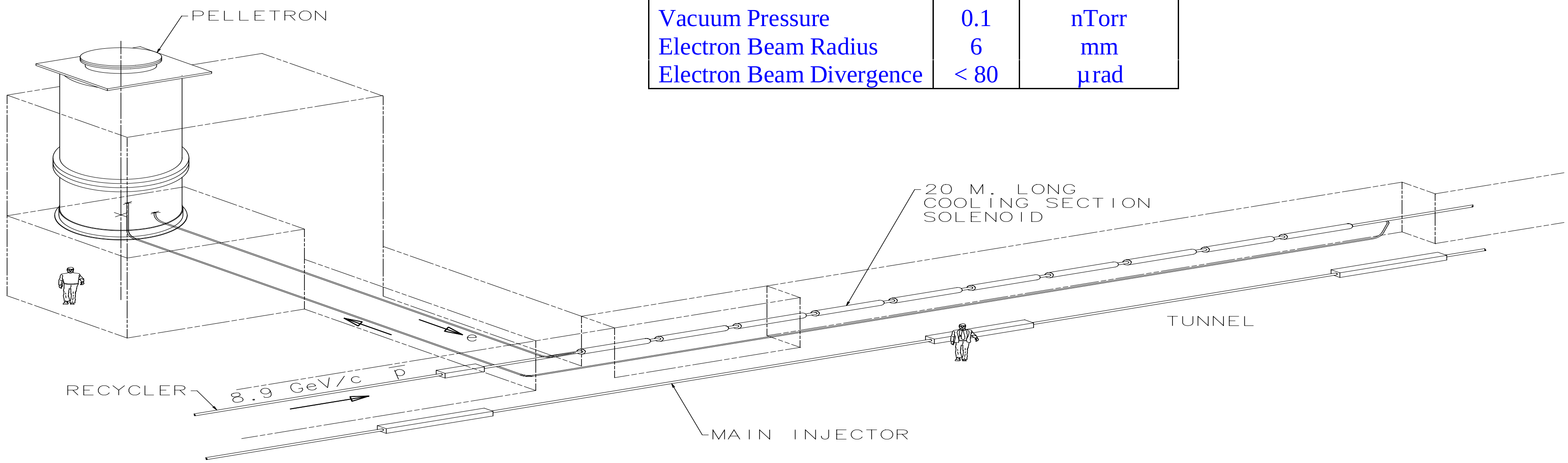
Recycler Electron Cooling

- Stochastic Cooling will be used in the Recycler at the beginning of Run II. It will be replaced with electron cooling.
- Because of the Recycler lattice parameters it is at least very difficult to increase the stochastic cooling system bandwidth.
- Electron cooling will relieve the Accumulator of having to cool the antiproton beam to its ultimate density.
- Electron cooling will make it possible to cool and recycle the high intensity antiproton beams required to approach a luminosity of 10^{33} cm^{-2} sec^{-1}.
- A substantial R&D effort is underway to understand the technology required to achieve cooling of an 8 GeV antiproton beam.

Schematic Layout of Recycler Electron Cooling

Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	200	G
Cooling Section		
Length	20	m
Solenoid Field	50	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	< 80	µrad



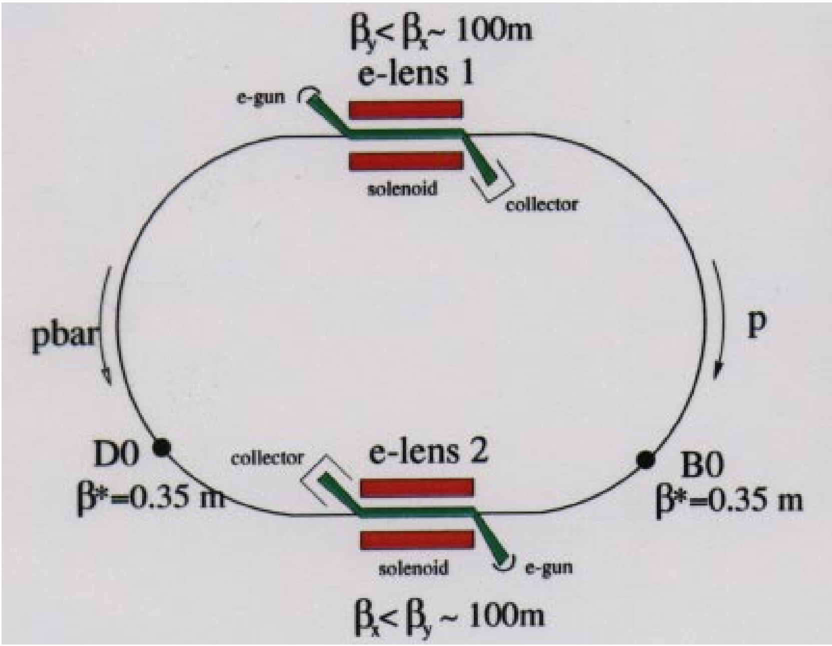
Accumulator to Recycler Beam Transfer (AP-5)

- At the beginning of Run II, the transfers will take place through the AP-1 line, the Main Ring remnant, and the Main Injector. This path is awkward not only because of the indirect route, but because this beam line is also used to transport 120 GeV protons to the production target.
- With 4x the antiproton flux, the reduction of the cooling requirement in the Accumulator implies transfers between the Accumulator and the Recycler every few minutes.
- A dedicated 8 GeV transport line between the Accumulator and Recycler may be essential.

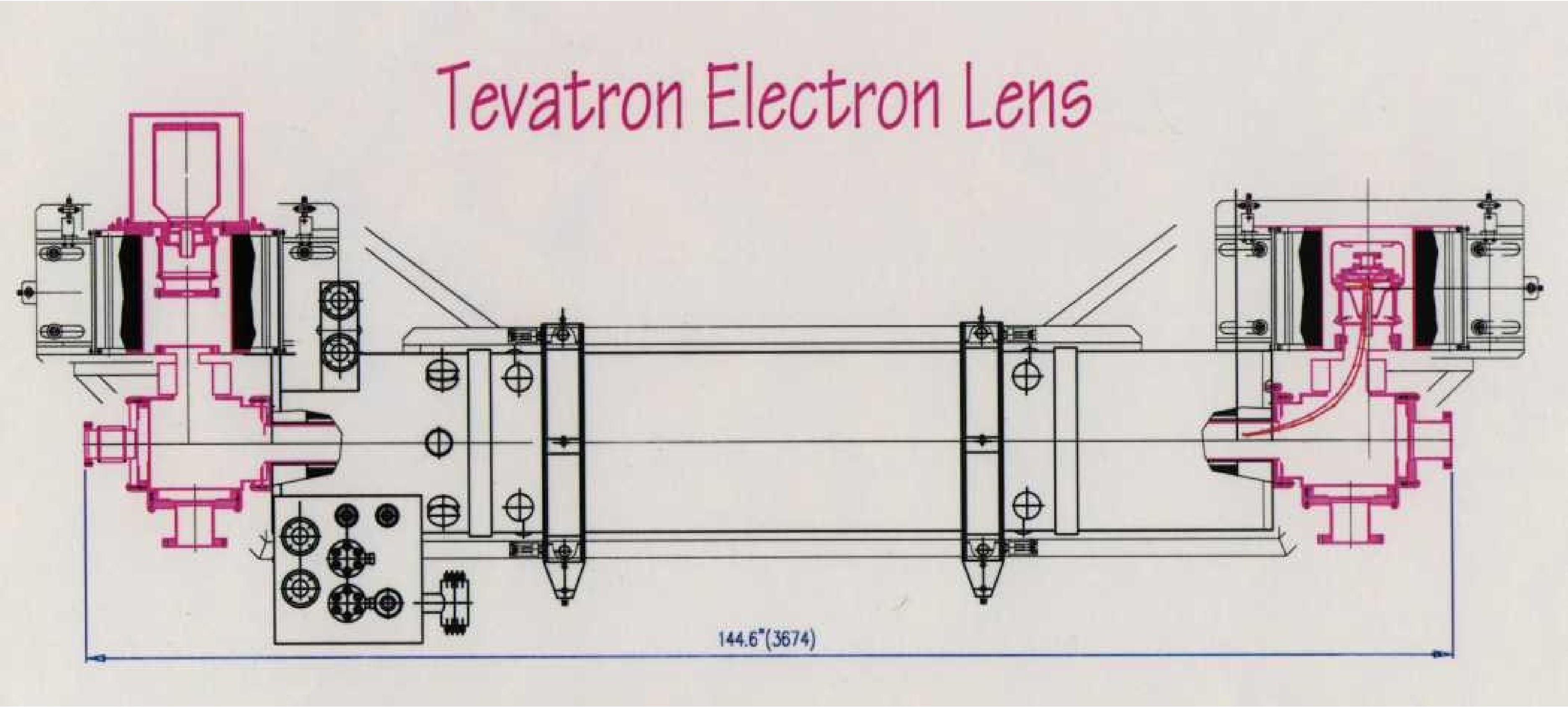
Beam-Beam Tune Shift Compensation

- The goal of the compensation project is to produce an electron beam whose negative charge will cancel the tune shift produced by the proton beam. The electron beam would be collided with the antiproton beam in a location (F49) remote from the interaction regions.

TEV Layout Cartoon

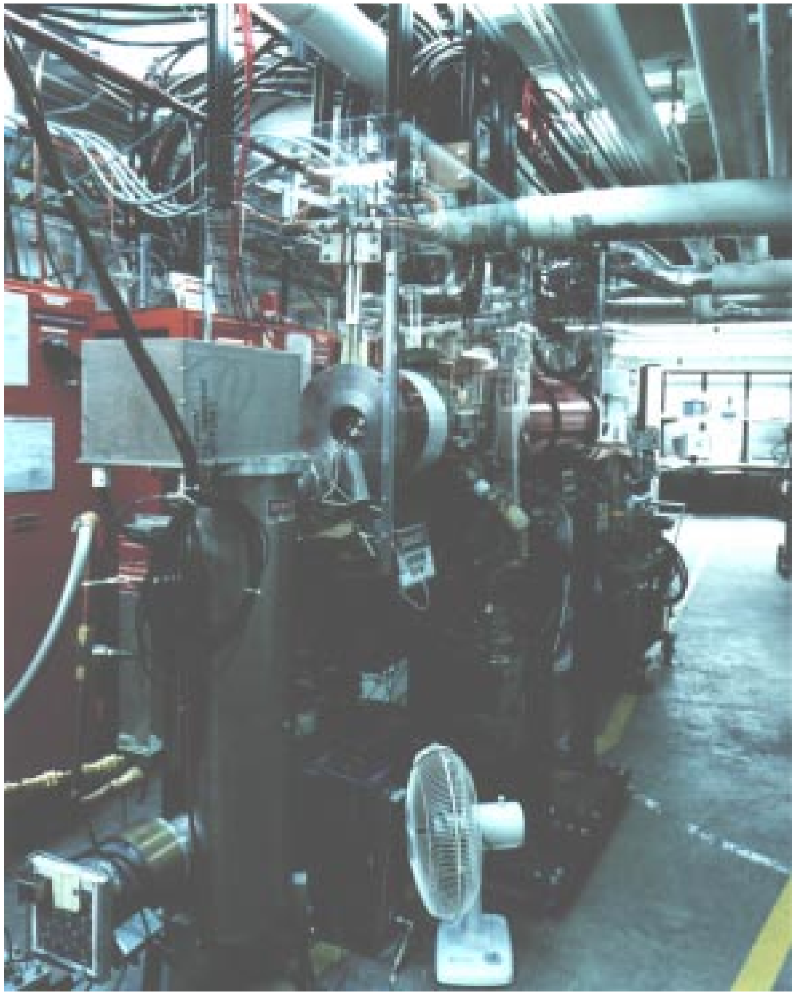


TEVATRON Electron Lens Prototype



TEVATRON Electron Lens Prototype

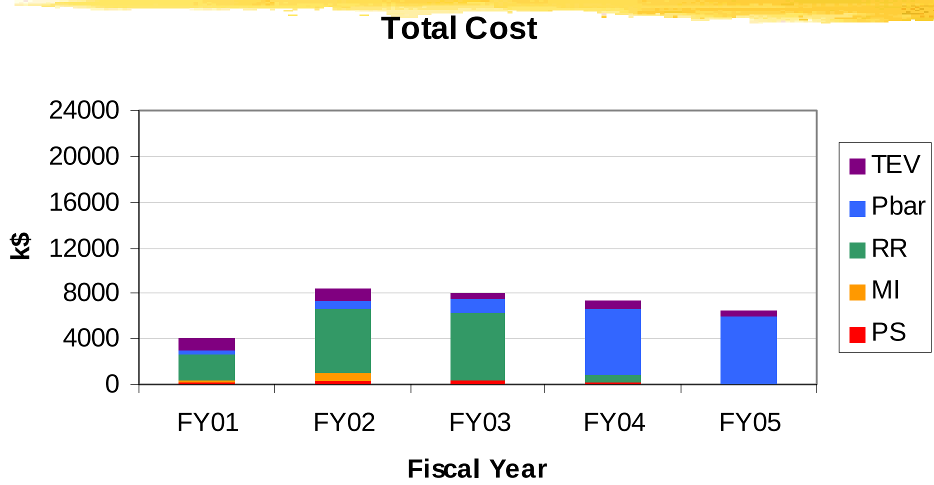
(located in LINAC basement)

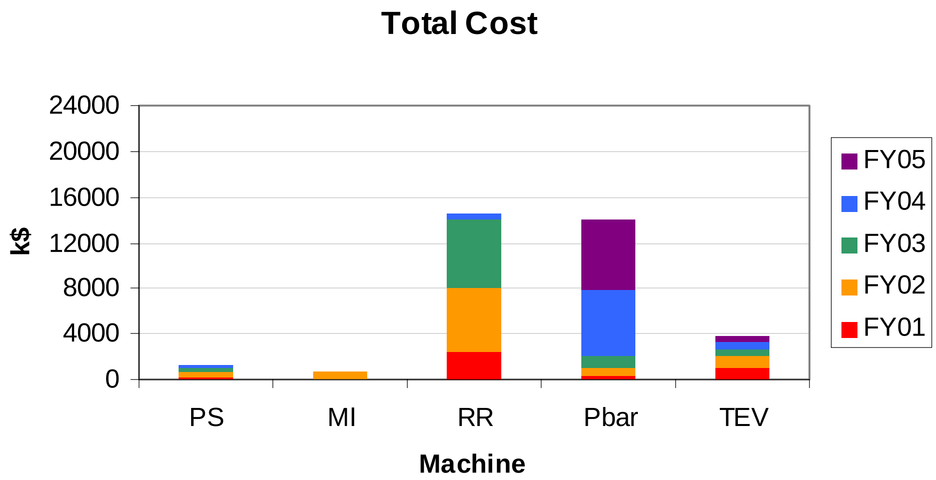


Run IIb Summary

- Increase the number of antiprotons in the collider by a factor of 2-3 over Run IIa
- More protons on the antiproton target
  - Slip stacking (~1.8 x)
- Better antiproton collection efficiency
  - Lithium lens Upgrade(~1.3 - 1.5 x)
  - AP2-Debuncher aperture increases (~1.5 x)
- Handle the Increased Pbar Flux
  - Debuncher cooling bandwidth increase
  - Accumulator Stacktail
  - Electron cooling in the Recycler
- Better Antiproton Transfer Efficiency

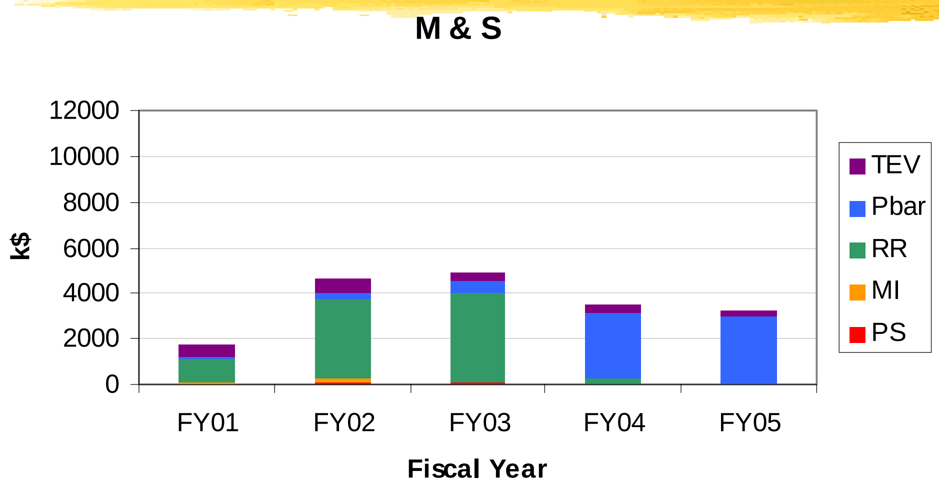
Total Cost for Run IIb

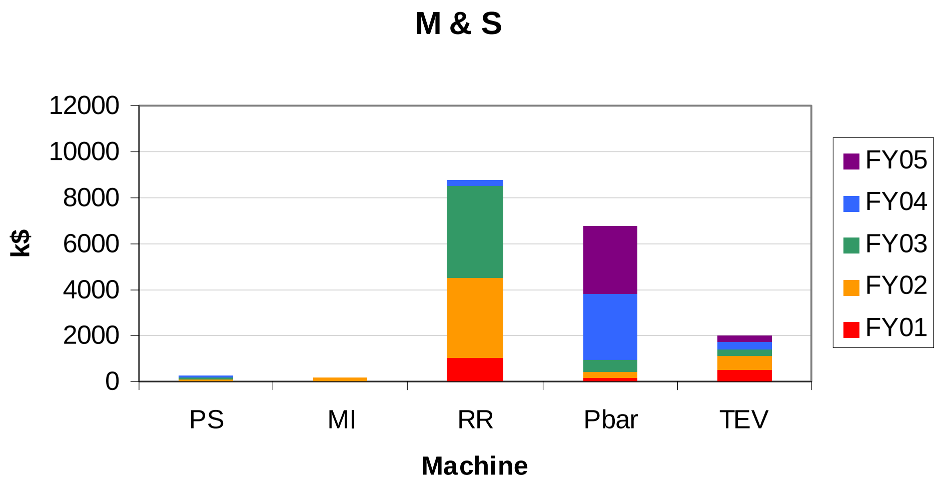




			Total			
	FY01	FY02	FY03	FY04	FY05	Total
PS	249	367	389	231	0	1235
MI	77	693	0	0	0	770
RR	2384	5637	5960	600	0	14580
Pbar	329	673	1128	5824	5987	13940
TEV	1000	1110	555	648	463	3775
Total	4038	8479	8032	7302	6449	34300

M&S Cost for Run IIb

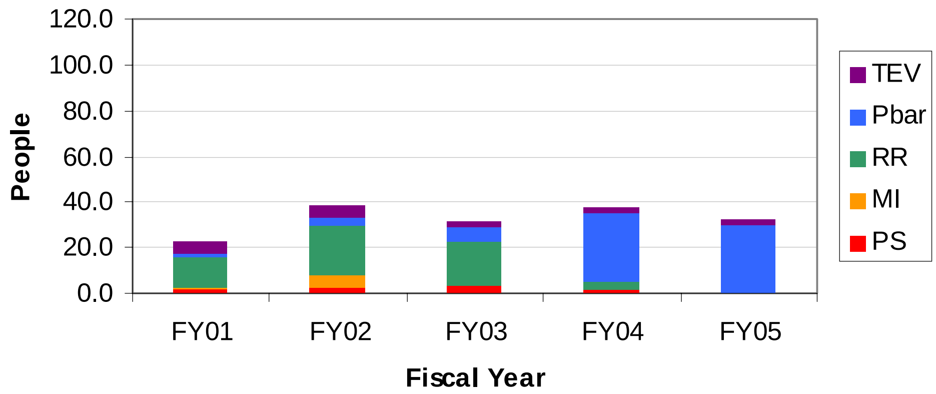




			M&S			
	FY01	FY02	FY03	FY04	FY05	Total
PS	43	67	73	38	0	220
MI	20	180	0	0	0	200
RR	1050	3500	4000	250	0	8800
Pbar	145	285	510	2890	2985	6815
TEV	500	600	300	350	250	2000
Total	1758	4632	4883	3528	3235	18035

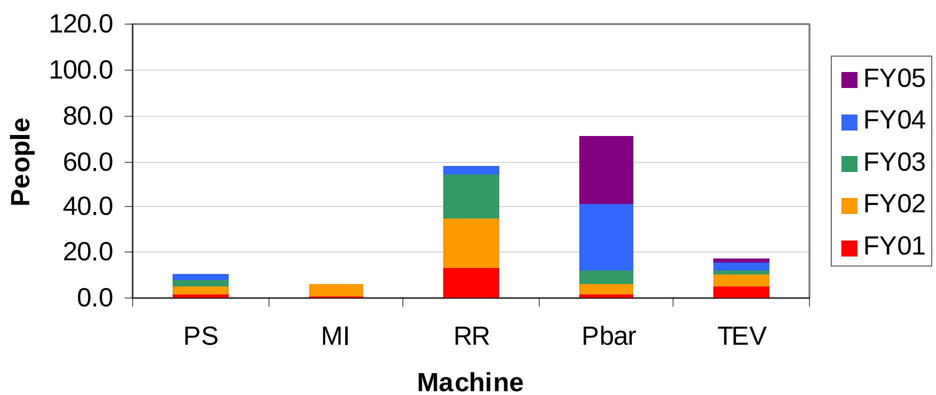
Labor Cost for Run IIb

Total Labor



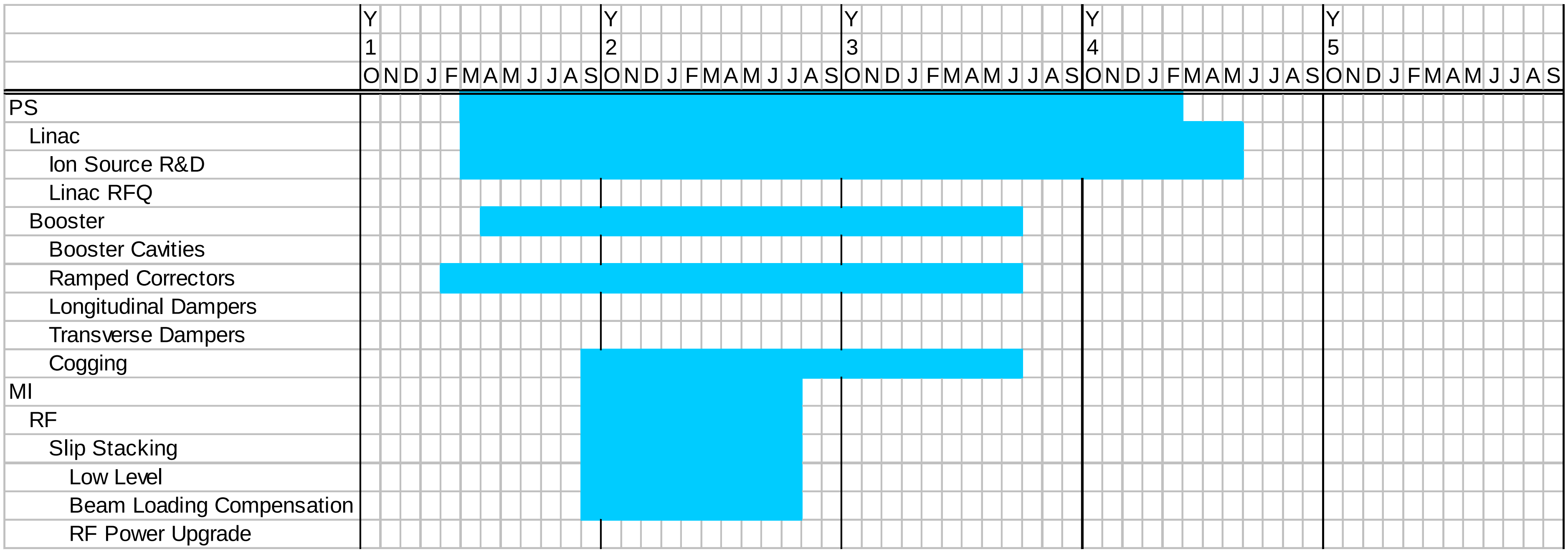
			Labor			
	FY01	FY02	FY03	FY04	FY05	Total
PS	2.1	3.0	3.2	1.9	0.0	10.2
MI	0.6	5.1	0.0	0.0	0.0	5.7
RR	13.3	21.4	19.6	3.5	0.0	57.8
Pbar	1.8	3.9	6.2	29.3	30.0	71.3
TEV	5.0	5.1	2.6	3.0	2.1	17.8
Total	22.8	38.5	31.5	37.7	32.1	162.7

Total Labor

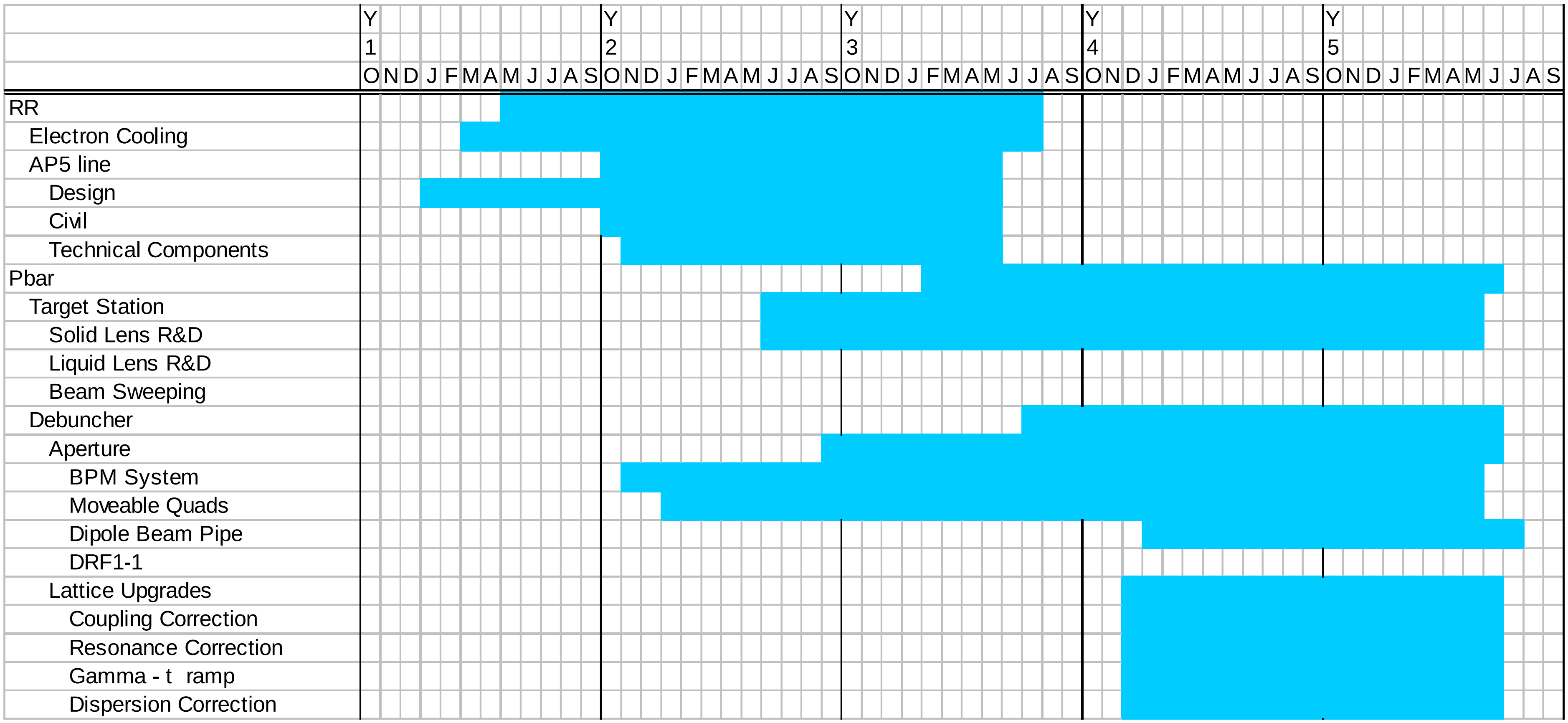


			Labor$			
	FY01	FY02	FY03	FY04	FY05	Total
PS	206	300	316	194	0	1015
MI	57	513	0	0	0	570
RR	1334	2137	1960	350	0	5780
Pbar	184	388	618	2934	3002	7125
TEV	500	510	255	298	213	1775
Total	2280	3847	3149	3775	3214	16265

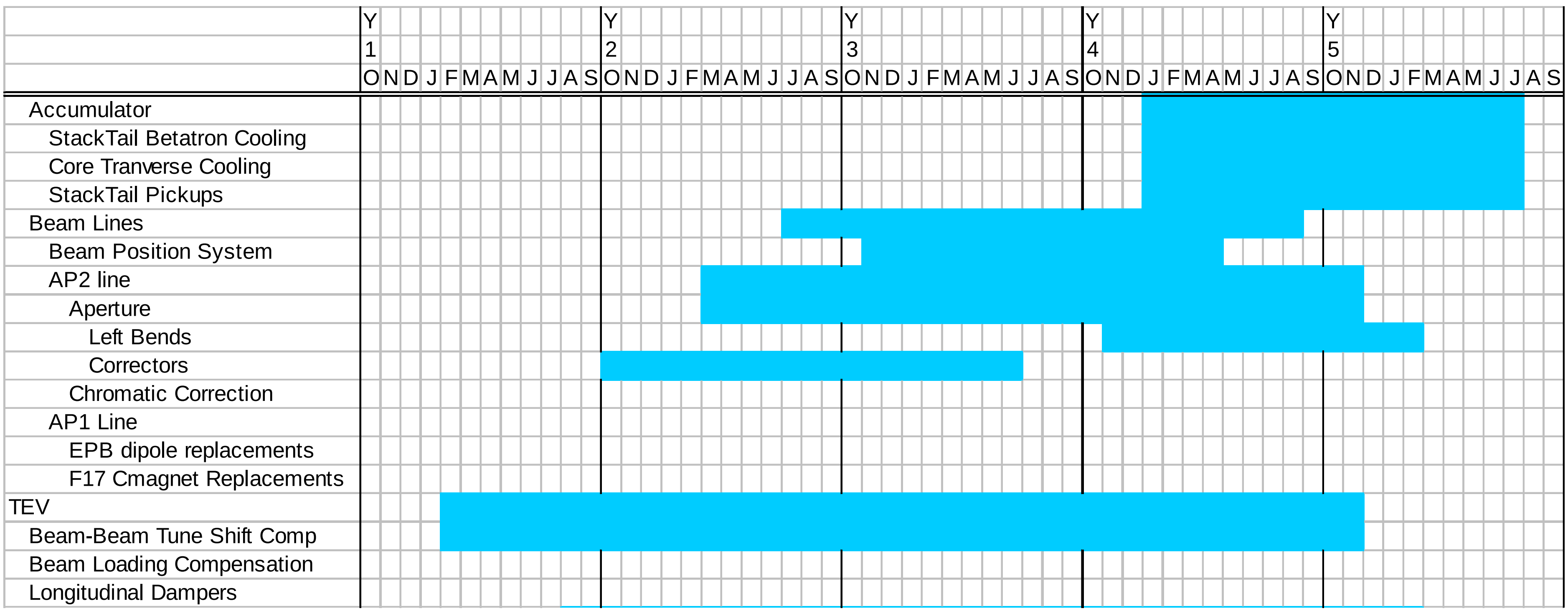
Run IIB Schedule



Run IIB Schedule

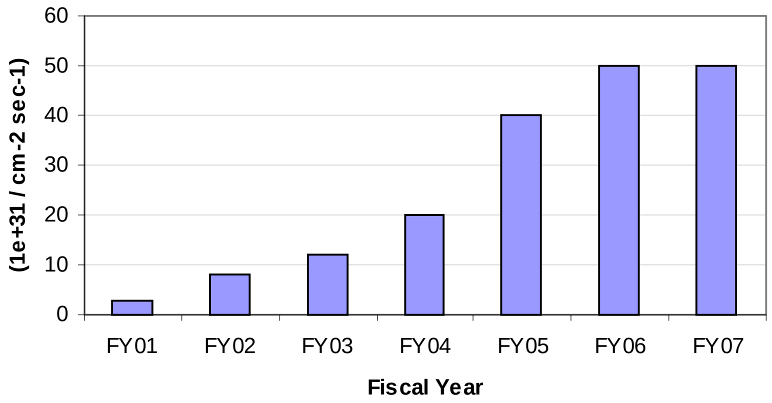


Run IIB Schedule

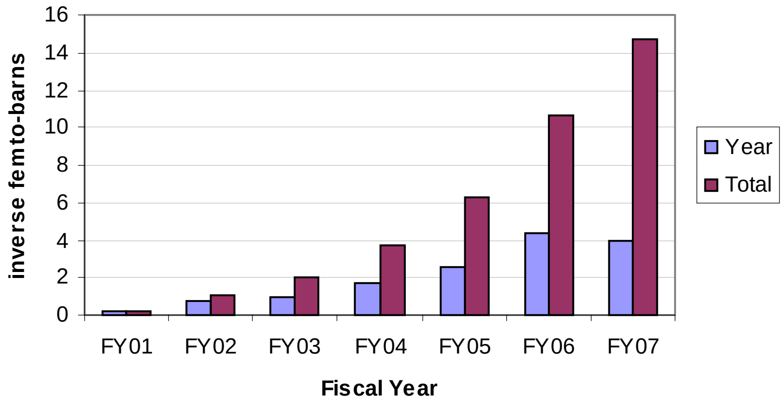


Run IIb Luminosity Schedule

Initial Store Luminosity



Integrated Luminosity



Initial Luminosity & Resources Spent